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EFFECT OF INSTABILITY DURING ROTATION ON PHYSIOLOGIC AND PERCEPTUAL-MOTOR FUNCTION

GENERAL DYNAMICS
Convair Division

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EFFECT OF INSTABILITY DURING ROTATION ON PHYSIOLOGIC AND PERCEPTUAL-MOTOR FUNCTION

FINAL REPORT

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FOREWORD

This document is the final report on a study conducted by Convair division of General Dynamics for the NASA Manned Spacecraft Center. This final report is submitted in full compliance with the requirements of Contract NAS 9-6986 under the National Aeronautics and Space Administration, Manned Spacecraft Center Procurement and Contracts Division, Houston, Texas. The work was completed under the Technical Monitoring of Richard E. Waite, MSC Biomedical Research Officer, and the Supervision of Dr. Bernard D. Newsom, assisted by James F. Brady and Thomas W. O'Laughlin.

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SUMMARY

The requirement for an artificial gravity space station has not been established because of the limited duration of space missions to date. The eventuality of such a system, however, is generally accepted on the justification of comfort, training, facilitation of mechanical operations, and the more natural environment it offers for prolonged missions. A rotogravity environment has been studied on the basis of radius requirement and rotational velocity limitations for crew habituation and performance. The added parameter that influences design and propellant costs is the STABILITY required for the crew to operate satisfactorily. The effect of perturbation during rotation is the subject of this study.

The study was completed in three tasks. Task I investigated the effect of rotation and sinusoidal perturbation on a seated subject performing a battery of perceptual-motor tests representative of the tasks required by an astronaut crew. Task II imposed the added factor of a rapid head motion upon the perturbating environment at high rates of rotation. The criteria were performance of a eye-hand response test and the time it took for the subject to fixate on a point display following the head turn. Task III was performed to assess the perturbation effects on the time it took for the habituation of a single perceptual element to rotation. The disorientation that results from a rapid head motion can be evaluated by the "Oculogyral Illusion" that occurs in a darkened room. An illuminated target appears to drift about and this motion is extinguished as habituation occurs.

Results of the three experiments indicate that sinusoidal motions of the magnitude anticipated in space stations should not complicate the performance of crew tasks that do not require the translation of a subject in that environment. Perceptual-motor performance was not degraded; rapid head turns caused no more decrement in performance during perturbation than in stable rotation; and the rate of oculogyral illusion extinction was the same, even though the extent was less, in the perturbating environment.

The consistency of results supports the hypothesis that perturbation during rotation creates a constant stimulus to the vestibular system and, as such, keeps the receptor in a partial refractory state which, in turn, raises the threshold for sensitivity to cross-coupled acceleration.

SECTION 1

INTRODUCTION

Certain basic requirements can be predicted for those future vehicle systems requiring multi-man crews to function optimally for long periods in space. A reliable life support system free from toxicological problems, for example, is a well-recognized requirement. A requirement not so well agreed upon is for artificial gravity to maintain the musculo skeletal and cardiovascular systems of the crew close to normal equilibrium for earth re-entry. Much of the thinking in this field has been about the immediate problem of relatively short duration manned space missions and it appears from available information that man can survive such exposure. However, there are advantages in addition to physiological support to be gained from creating an inertial field. Assembly of parts, repair of equipment, preparation and ingestion of food are all facilitated by an inertial directing force. Personal hygiene can be more closely controlled and sanitation is easier to maintain if dirt and fluids collect on the floor. Artificial gravity also allows the enjoyment of an occasional shower which is usually a priority desire in confinement studies. All of these considerations take on new importance when mission durations are extended to a year or more, provided that such missions are within engineering feasibility and physiological tolerance.

1.1 ENGINEERING GUIDES

To be prepared for possible development of these future artificial gravity systems, it is necessary to start research on the support technologies. The type of information design engineers require concerning man's functional tolerances in these environments does not presently exist.

Though the response of the otic labyrinth to both weightless and artificial gravity environments certainly requires further elucidation, this study has been directed primarily toward questions concerning man as a functional system in these environments. Engineers choosing optimal man-machine tradeoffs must know the work potential of man in rotating vehicles of various dimensions and force field characteristics. These guidelines must be realistic not only for the large orbiting vehicles of the future, but - even more acutely - for experimental systems that could be included in the Apollo Application Program and as backup concepts for vehicles now in the definition phase.

Loret[1] and Dole[2] have listed many engineering constraints imposed by the crew during rotation but neither considered stability of the vehicle as a design limitation. In providing a habitable rotating space vehicle, however, stability could be no less important than angular velocity, radius, g-level or rim velocity. In a rotating space vehicle, vehicle precession as well as head rotation could stimulate the crewman's labyrinth. Vehicle instability could be anticipated to lower the permitted angular velocity as it seems reasonable that the stimuli to the labyrinth due to vehicle instability would complement that due to the crewman's active head movements.

Vehicle precession predicates caution in assigning spin-rate ceilings at this time. Investigation of the total dynamic environment in a simulated rotating vehicle in relation to habitability and crew performance is necessary. Without such ground work, design engineers must work in an arbitrary manner; this could be costly and mission limiting. Kurzhals[3] and Larson[4] have lent theoretical and empirical consideration to the engineering problem of instability in the manned rotating vehicle. Coupled to such efforts there should be tests of crew performance as a function of instability, as well as of the previously considered parameters.

Disturbances such as docking impacts and active or passive changes in crew or hardware mass, may cause many combinations of structural and force field oscillations which could be detrimental to crew function. As stability of a rotating space vehicle is related directly to its total mass, the relatively light state-of-the-art vehicles would be particularly susceptible to instability from mass disturbances. In a discoid or toroidal vehicle rotating about its principal Z axis, a crewman aligned with one of the transverse X or Y axes could be subject not only to the disturbing effects resulting from his active head movements relative to the spin plane, but also to a variety of oscillating forces beyond his active control.

Any impulsive torque applied about either one of the two transverse axes of the rotating vehicle would result in a wobble (defined as an oscillatory curvilinear movement) about both X and Y transverse axes. The amplitudes of these oscillations would be directly proportional to the angular impulse and inversely proportional to the moment of inertia around the transverse axis normal to the axis of torque. Figure 1-1, taken directly from Kurzhal's LRC report[3] demonstrates a typical wobbling response to a movement of a crew member two feet out of the plane of spin in a 30-foot station. These data were derived using a scale model and programmed movements of lumped masses.

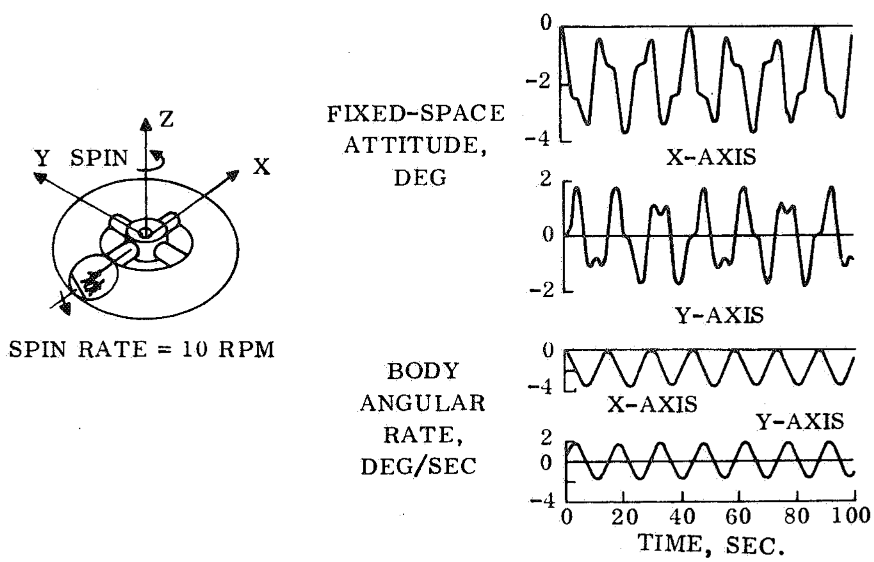


Figure 1-1. Disturbance Effects for 30-Foot Space Station Configuration as Determined at L. R. C.[3]

Figure 1-2, from the same report, lists data from similar experiments using an entire crew performing maximal excursions at running rates. A reduction in vehicle size causes a dramatic increase in wobble. It is emphasized that these figures represent an uncontrolled station; several methods of active or passive dampening can be used to increase stability, but they entail weight and power penalties.

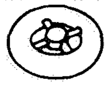
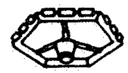
TYPE OF DISTURBANCE	30-FOOT STATION  CREW: 2		150-FOOT STATION  CREW: 21	
	DISTURBANCE EFFECTS			
	MAX WOBBLE ANGLE, DEG	APPARENT STA. ROLLING, DEG	MAX WOBBLE ANGLE, DEG	APPARENT STA. ROLLING, DEG
RADIAL CREW MOTIONS	9	0 TO 12	0.7	0 TO 0.8
TRANVERSE CREW MOTIONS	13	0 TO 5	1	0 TO 0.3
CIRCUMFERENTIAL CREW MOTIONS	108	80 TO -80	3	3 TO -3
DOCKING IMPACTS	2	2 TO -2	0.05	0 TO 0.04

Figure 1-2. Disturbance Effects for Two Space Station Configurations as Determined at L. R. C.[3]

An inertial unbalance produced by an uncompensated mass movement along a transverse axis within the plane of spin will couple with the moment of inertia about the spin axis to produce a disturbance about that transverse axis that is directly proportional to the initial vehicle spin rate and the product of the inertias of the transverse and spin axes. This generated spin coupled with the initial vehicle spin will produce varying angular velocity patterns. A crewman aligned with this axis will experience the illusion of complex and ever-varying tilting of the floor as his body perceives the resultant of the linear acceleration oscillating along his longitudinal body axis and the linear acceleration normal to this axis. The linear acceleration normal to this axis would trace the vectorial pattern defined by Larson[4] and shown in Figure 1-3. Simultaneous dynamic mass unbalances along both transverse axes (the anticipated situation) would complex the vector pattern and the resulting disturbances.

1.2 REQUIREMENTS

The primary disturbances that may result from vehicle instability are:

a. wobbling, the precession of the space vehicle spin axes relative to space-fixed coordinates, and

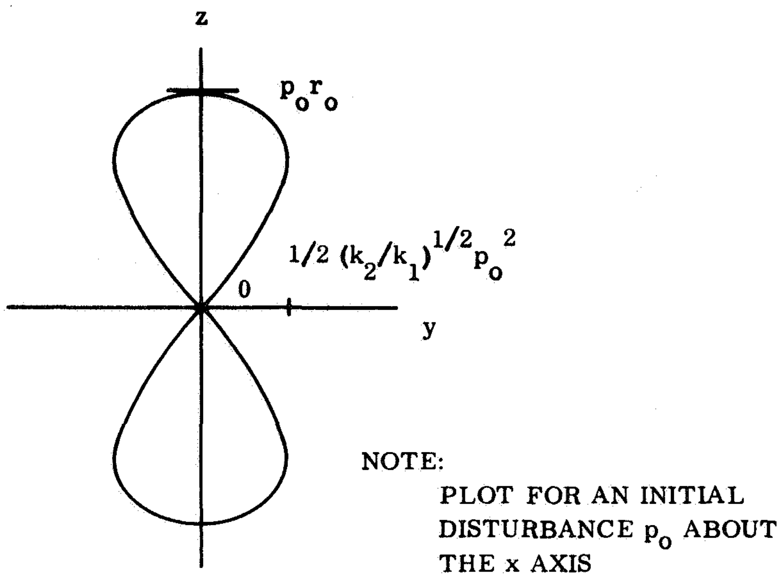


Figure 1-3. Gravity Vector Trace in the YZ Plane[4]

b. Rotogravity* oscillation, the precession of the vehicle angular momentum vector. These instability factors may occur singly, sequentially, or simultaneously. Stability, therefore, presents a critical and complex biofunctional problem to assess. It is, moreover, a quality that can be assured only at the expense of vehicle power and responsiveness, making the amount of instability that can be permitted without crew performance degradation an important design contingency.

Therefore, simulation difficulties and unavoidable artifacts should not preclude the inclusion of stability in defining the vehicle biofunctional design envelope. Even "ballpark" guidelines are better than arbitrary design choices.

To expedite the definition of these guidelines, the "black box" approach has been used in preference to a purely analytic investigation[5,6,7]. For this type of study a significant number of subjects are required to perform appropriate tasks within a simulator that is a reasonable facsimile of a rotating space station. By varying the dynamic characteristics of the environment (angular velocity and stability) we may obtain

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*"rotogravity" is used to describe the inertial force derived by rotating the vehicle to produce an artificial gravity by centrifugation.

guidelines in terms of crew performance. In this way realistic crew requirements for stability systems can be estimated, enabling the engineer to proceed on design aspects of the program.

In the previous contract, NAS 9-5232, it was demonstrated that an increased perceptual-motor performance decrement occurred with an increase in the interplanar angle separating the plane of subject head turn and the plane of simulator spin. That study, however, involved a stable simulator which was not perturbating. The constantly varying passive orientation of personnel to the environmental force field in the perturbating situation could have one of several effects upon the adjustment pattern witnessed in the previous contractual study. Depending upon the degree of specificity linking the adjustment to the initiating stimulus, the ever-changing orientation of subject to environmental force field might slow the process of adjustment. This would make the various head-turn orientation test sequences more traumatic, causing an increased performance decrement relative to a non-perturbated rotating environment. A second alternative might be that the adjustment process to a rotational stimulus is a suppression process that is categorical for all subject orientations, in which case the constant interaction of the subject's labyrinths with the environmental force field would hasten the adjustment process, resulting in improvement of relative performance. The third possible effect considered was that of a reduced vestibular sensitivity due to the sensor being in a partially refractory (or recovery) state because of the constant passive motion of the subject. Such an effect would manifest itself in degraded performance during sequences involving rotation alone, but as improved performance, due to reduced stress, during sequences involving rotation and perturbation.

SECTION 2

APPROACH

In a rotating environment the crew is subject to Coriolis accelerations that may result in disorientation, vertigo and motion sickness.[8,9,10] Even without voluntary movement on the part of the crewman, similar effects may be caused by the vehicular perturbations resulting from internal or external mass unbalances in an insufficiently stabilized vehicle. These perturbations - similar in magnitude and effect to the movements of a ship at sea - produce cue conflicts in the orientation triad of vision, inner ear, and deep proprioception.

2.1 INFORMATION GOAL

The problem of stability in a rotating space vehicle has received little study in biologic laboratories, probably because of the relatively sophisticated simulator required. It has not been similarly neglected as an engineering consideration and deserves comparable study by workers in bioastronautics.

The low-frequency oscillations involved in perturbation have been thought to affect macular sensors, as well as cupular sensors, while the Coriolis accelerations appear to be detected primarily by the cupulae. Those functions found in previous tests to be sensitive to Coriolis accelerations might be expected to degrade even further due to the simultaneous perturbation of the rotating environment. An analysis of these degradative effects should include:

a. An evaluation of the types of active and passive biodynamics causing degradation[11].
b. A determination of the extinction rate of the vestibulo-ocular illusions causing performance degradation[11,12].
c. Quantification of changes in biofunctional efficiency by use of basic biofunctional testing[7,12,13].

SECTION 3

MRSSS EXPERIMENTATION

On the basis of the studies that have been completed using the Manned Revolving Space Station Simulator (MRSSS), it has been concluded that man can adjust to, and resist performance decrement in, a stable rotogravity environment of six RPM; that the functional adjustments required by his passing into and out of a rotating environment can be eased by graduating such transitions; that prior to making the physiologic adjustments required by such transitions he can adjust his behavior very rapidly so as to perform optimally; and that proper location and orientation of control and display hardware can maximize his performance, especially during the adjustment to force-field changes.

A rotating spacecraft, exposed to either static or dynamic unbalances, would respond gyroscopically with a tendency to oscillatory precession. Presumably the spacecraft will have stabilization systems to counter such disturbances but it is important to know to what extent this control must be effective and what the "off-nominal" operation tolerance of the crew is in event of system failure. In a rotating environment this oscillatory precession (wobbling) may create disorientation similar to that resulting from active movements by passively moving the crew. This wobbling can be effectively simulated by oscillation of the MRSSS as it rotates. To facilitate this simulation, the hydropneumatic ram system used to incline the MRSSS on its trunnions was modified, making it capable of executing sustained programs of oscillation. (See Appendix A for MRSSS description.)

With the capability to simulate an oscillating, rotating environment, it was then necessary to select performance tasks appropriate for determining functional limits within such an environment. Experience from previous testing in the MRSSS has demonstrated that performance adjustment during rotation occurs quite rapidly.

3.1 GENERAL PROGRAM PLAN

The trunnioned cabin of the Convair Manned Revolving Space Station Simulator (MRSSS) can be inclined so that the resultant force field is perpendicular to the center of the floor. It also provides a means to perturb the cabin and vary the angular velocity so inertial forces within the chamber simulate the vector patterns predicted for various sizes and configurations of spacecraft rotated to produce artificial gravity. No information on how such perturbations affect general performance is available; this study is the preliminary effort to generate such data. The perturbations are expressed as deviations of the inertial vector about the subject's Z axis so the results of the study can be applied to vehicles of any radius. Studies by other authors[14] indicate that the problem is virtually radius-independent because of the relative vestibular sensitivities to the motions concerned.

The following three tasks were completed to study the effects on performance of perturbation during rotation.

3.2 TASK I

Baseline measurements were made on 12 subjects under static conditions. Biofunctional efficiency tests were administered repeatedly until a consistent score was obtained. The tests were then repeated while the subject was exposed to (a) ±3 degrees, 0.1 cps perturbation, (b) 6 RPM at a 20-foot radius, and (c) simultaneous perturbation and rotation.

3.3 TASK II

The technique developed on the previous contract (NAS 9-5232) was used as a performance measurement to assess the importance of orientation within an inertial force field perturbed at 0.1 cps. Ten subjects were tested following baseline measurements, their performance was measured after making Y-axis head turns at 0 degrees, 45 degrees, and 90 degrees to the spin plane. Regression slopes were determined at (a) ±3 degrees, 0.1 cps perturbation, (b) 12.4 RPM, and (c) 12.4 RPM and ±3 degrees, 0.1 perturbation.

3.4 TASK III

Vestibular habituation was compared for a specific head movement while subjects were exposed to rotation and perturbation independently and in combination. Sixteen subjects were exposed to 8 RPM for four hours; every 15 minutes a frontal (X-axis) head turn was made to the right shoulder and the duration of oculogyral illusion (OGI) recorded. The extinction rate of the OGI was compared at 0 degrees perturbation and then with ±3 degrees perturbation at 0.1 cps. The first eight subjects were tested with 0 degrees perturbation first and with ±3 degrees perturbation two weeks later. The second eight subjects were tested in reverse order. All subjects received aural caloric tests before and after rotation.

SECTION 4

TASK COMPLETION

4.1 TASK I: PERCEPTUAL-MOTOR RESPONSE TO ROTATION, PERTURBATION AND COMBINED ROTATION AND PERTURBATION.

A survey of possible tests and test batteries was made to find a series of appropriate performance measurements. Both the Air Force and NASA[15] were found to be developing "face value" type consoles for the specific purpose of evaluating man's control performance in the types of environment of interest to this study.

Arrangements were made to borrow a unit of the Perceptual-Motor Console Model 766* from the Manned Spacecraft Center, Houston, in conjunction with the performance measurements being made under NAS 9-5232 and for use in a pilot perturbation study being conducted in the MRSSS. Following the pilot study, permission was obtained from MSC to perform this study as part of the experimental effort.

4.1.1 <u>METHOD</u>. The MRSSS is instrumented and equipped to permit continuous rotational studies of four subjects for unlimited periods of time, and is described in greater detail in previous reports[6] and Appendix A. For this study, the room was spun at 6 RPM, an angular velocity which previous studies had determined to be realistic for a stable rotogravity spacecraft of projected dimensions.[7] At this spin rate and with an effective radius of slightly more than 18 feet, a resultant 1.04 g was imposed on the study participants and the inclination of room vertical (about which perturbation took place) was 14 degrees. A perturbation profile of 0.1 cps and ±3 degrees was selected to simulate a reasonable maximum to be encountered in projected rotogravity vehicles.[3]

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*Fabricated under Contract No. NAS 3-1329 by Biotechnology, Inc., Arlington, Va.

The testing consoles were designed for NASA by J. F. Parker, Jr., et al[15], to integrate devices for a battery of tests that measure the primary dimensions of perceptual-motor performance. The tests used are based on well-established techniques with well-documented interpretations of results. Appendix B presents a detailed discussion of the tests. Primary dimensions to be measured were chosen to (a) specify abilities underlying complex perceptual-motor performance, and (b) relate significantly to tasks and duties to be performed by spacecraft personnel.

The two consoles (subject's and examiner's) are shown in Figure 4-1. Additional test items and accessories included are the (a) manual dexterity test, (b) stylus and mirror-tracing maze, (c) mirror-tracing visor and (d) finger dexterity test. Details of the tests are presented in Appendix B.

Figure 4-1 shows the subject's and examiner's consoles arranged so the examiner can visually monitor both consoles and the subject. For this test the subject was seated in the center of the simulator, the position at which the gravitocentrifugal resultant was perpendicular to the floor. The subject faced tangentially, in the direction of spin, as he would if optimally positioned for monitoring a control-display console[13] in a rotating space vehicle, and in a position in which he would be perturbated from side to side by vehicular wobbling.

Table B-1 in Appendix B (taken directly from reference) summarizes the selected perceptual-motor ability factors and their categories.[15] "Adequacy of identification" indicates the results of the factor-analytic study. For a test to be considered, it had to load* at 0.30 or above on the primary factor or ability. If the test was not considered pure (loading only on one factor), secondary factors had to load at 0.30 or above.

4.1.2 BACKGROUND. Previous studies indicated that acceleration produced by the product of angular velocities resulting from head turning and vehicle rotation reduced performance in a rotating environment and that this reduction was due in part to visual location of the task display.[12] Perturbation of the subject during rotation can theoretically

*"Loading" designates the degree of specificity for measurement of a particular ability.

Figure 4-1. Perceptual Motor Test Consoles

elicit similar labyrinthine response from resultant velocity products. Performance could therefore be degraded without movement on the part of the subject (passive motion); however, previous testing had also demonstrated a rapid adjustment to the oscillating force field[5] (rotary pursuit tests) and fast recover following forced head turns,[11] so it might be anticipated that adaptation would result from sinusoidal perturbations during rotation. If such adjustment could be determined, the requirement for spacecraft stabilization would be reduced.

4.1.3 PURPOSE OF THE STUDY. The purpose of the study was to determine the effect that perturbation plus rotation has on performance of perceptual-motor tasks by subjects in a stationary mode with respect to the vehicle interior.

4.1.4 PROCEDURES. The MRSSS was used to test the subject for performance while (a) static, (b) perturbating, (c) rotating, and (d) rotating with perturbation. Perturbation of ±3 degrees was around the inclined resultant at 0.1 cps. Rotation rate was 6 RPM.

The NASA perceptual-motor test console* was used and all 18 tests were performed. The console was located at the simulator center with the subject facing the leading bulkhead. The subject was seated in front of the console with the test conductor immediately behind him. Each subject practiced on the console for a minimum of three sessions prior to testing on the centrifuge. At the end of each session a score was obtained to determine state of learning. No subject was tested that had not reached a learning plateau on each test.

Fifteen subjects were scheduled for testing. The results from the first twelve tested successfully were used. The testing order was as follows:

Subject No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Static	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A
Perturbate	B	B	C	C	D	D	B	B	C	C	D	D	B	B	C
Rotate	C	D	B	D	B	C	C	D	B	D	C	B	C	D	B
P & R	D	C	D	B	C	B	D	C	D	B	B	C	D	C	D
Static	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E

A ⟶ E order of testing

*NASw-1329 - Perceptual Motor Performance Console Model 766 described in Appendix B.

4.1.5 RESULTS. The tests were performed on twelve subjects without difficulty. Subjects were not distressed by the environment and appeared to enjoy the testing procedure. The scores, shown in Figures 4-2 through 4-6, are arranged into groups with common test objectives.

The test console was quite reliable during the tests; the only problems encountered were as follows: One micro-ampere meter failed to work for time-sharing and perceptual-speed tests and was replaced. The camswitch programmer was subject to failure unless it was cleaned regularly. Operation of some tests required considerable practice before consistent scores were reached and, even after achieving consistency, it was found that some subjects demonstrated increased capability in the post-dynamic test period.

4.1.5.1 Fine Manipulative Abilities (Figure 4-2). Significant decrement in performance ($P < 0.02$ from t-test two-tailed comparison) from rotation (R) to rotation plus perturbation (RP), due exclusively to the AHS test.

a. Arm-Hand Steadiness (AHS): Decrement from R to RP significant ($P < 0.001$ by two-tailed t-test). This is to be expected on the basis of test mechanics and dynamic environment. No requirement of movement by subject obviates interaction with rotation, but passive movement due to perturbation reduces steadiness.

b. Wrist-Finger Speed (WFS): No change. No requirement for head movement and insignificant hand translation preclude substantial rotational effects. Low accuracy requirement precludes RP effects.

c. Finger Dexterity (FD): Results and explanation similar to WFS.

d. Manual Dexterity (MD): Shows a nonsignificant decremental change associated with R. In this test there occurs a nodding of the head as the subject shifts attention from insertion of the block in the board to rotating the block in his hand. At 6 RPM this nodding approached a plane of 90 degrees to the spin plane of the simulator.

S_1 THRU S_3 = THREE STATIC TRAINING SESSIONS
S_4 = PRE-DYNAMIC STATIC
P = PERTURBATION (0.1 CPS, ±3°)
R = ROTATION (6 RPM)
RP = ROTATION + PERTURBATION
S_5 = POST-DYNAMIC STATIC

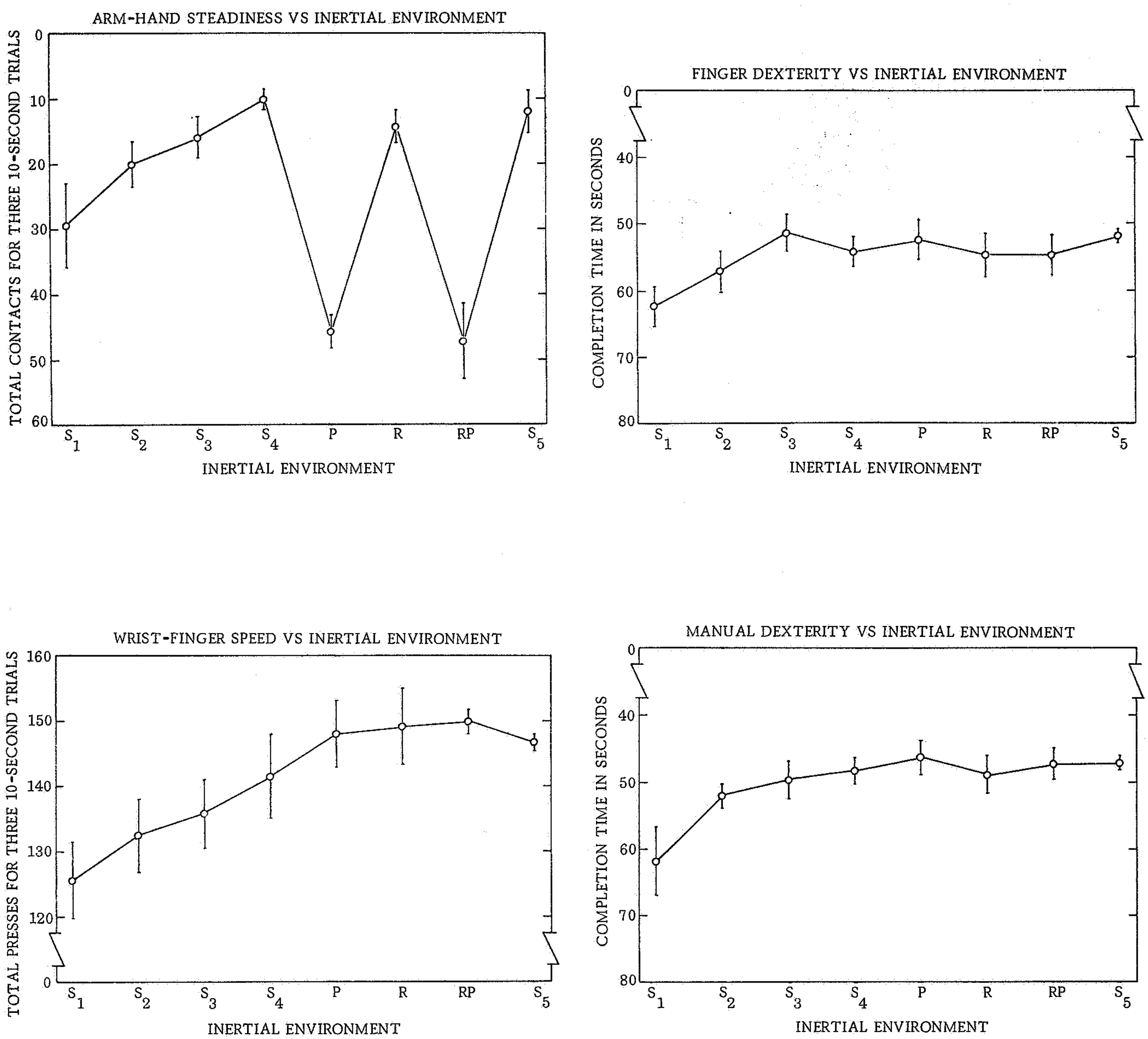


Figure 4-2. Fine Manipulative Abilities ($\overline{X}$ ±1 S. E. for N=12) Versus Inertial Environment

4.1.5.2 Gross Positioning and Movement (Figure 4-3). This category shows overall decrement with rotation (R or RP), suggesting a response to proprioceptive Coriolis effects.

a. Position Estimation (PE): The absence of improvement with the addition of perturbation suggests that the decrement during R is primarily due to the mechanical effects upon reach.

b. Response Orientation (RO): This test shows little apparent decrement with R relative to baseline. As in PE, the only disparity is the improvement with perturbation relative to the other inertial environments.

c. Control Precision (CP): No significant change.

d. Speed of Arm Movement (SAM): The test requires an appreciable radial translation, but no rapid head movements nor great accuracy; the results, therefore, would be anticipated to reflect some arm deflection by Coriolis action.

e. Multilimb Coordination (MLC): No significant change.

f. Position Reproduction (PR): In contrast to PE, the opportunity for a visually directed reach prior to a blind reach in this test appears to have eliminated much of the error due to rotation.

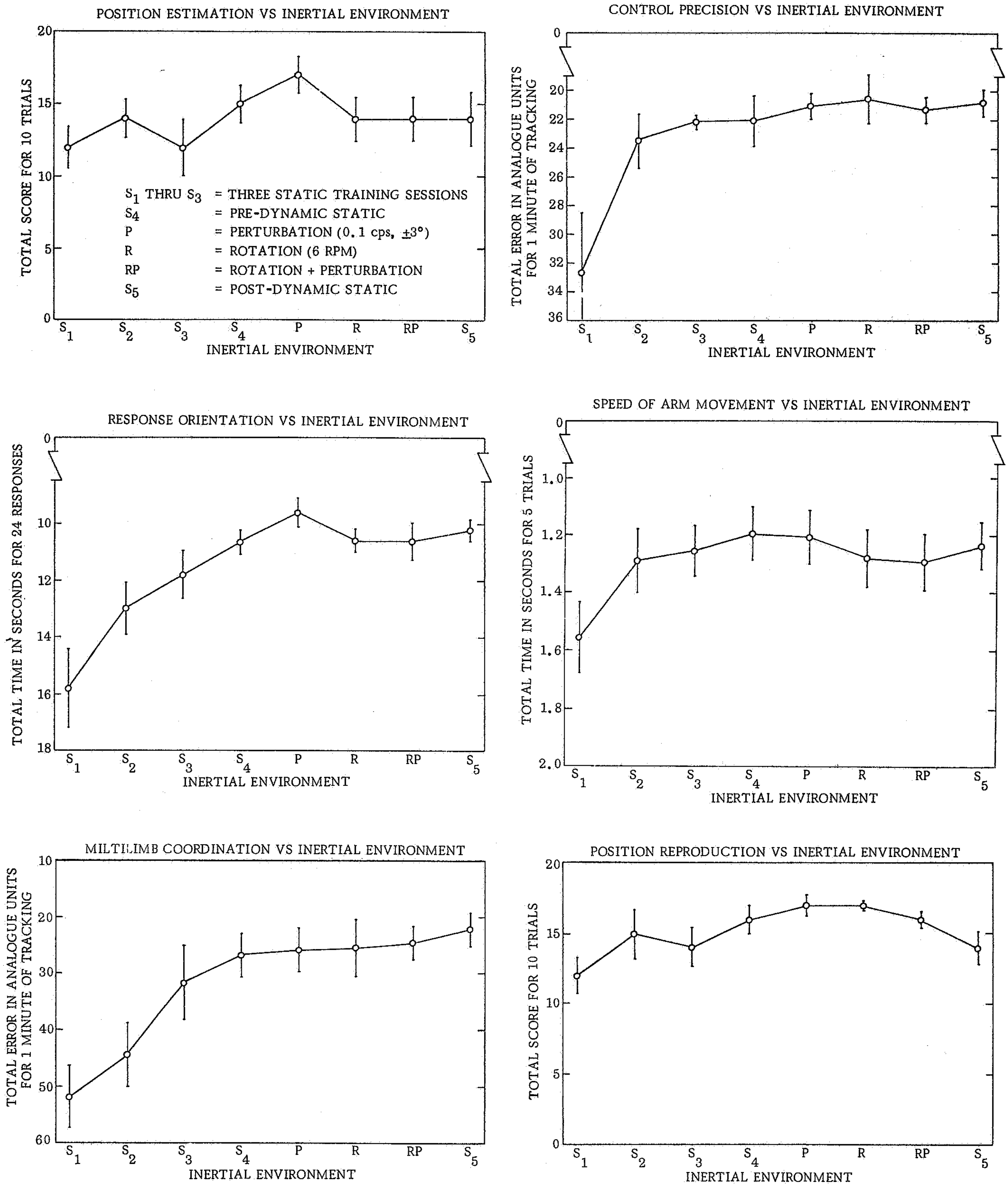


Figure 4-3. Gross Positioning and Movement ($\bar{X} \pm 1$ S. E. for N=12) Versus Inertial Environment

4.1.5.3 System Equalization Abilities (Figure 4-4). The overall relative decrement in performance during R is due entirely to the similar patterns in tests MA and MP.

a. Movement Analysis (MA) and Movement Prediction (MP): Biodynamically identical, these tests require no specific head or limb movements that might be sensitive to the environmental dynamics. They appear to require rational analyses that may be sensitive to either random head movements incidental to the specific test and/or the effects of preceding tests' environmental interactions.

b. Rate Control (RC) and Acceleration Control (AC): In contrast to the other tracking tests (RC, CP and MLC), the degree of difficulty makes AC sensitive to all three dynamic environments.

4.1.5.4 Perceptual-Cognitive Abilities (Figure 4-5). This category shows a relative decrement during rotation (R or RP) due primarily to the Time Sharing and Perceptual Speed Accuracy tests.

a. Perceptual Speed Time (PST): Though requiring a similar subject-console orientation to that of the Time Sharing test, PST, due to the requirement for accuracy, in most instances forces the subject to make greater amplitude head turns to monitor the two meters with foveal vision. The effects of this are apparent during rotation.

b. Perceptual Speed Accuracy (PSA): There is a significant sensitivity of this parameter to perturbation during rotation.

c. Time Sharing (TS): Monitoring of the two meters in this test requires only near-peripheral vision; the amplitude of head turns can be attenuated to near zero. Decrement in performance would then be anticipated primarily when RP combines the oscillatory shifts in parallax and the perceptual uncertainty resulting during rotation.

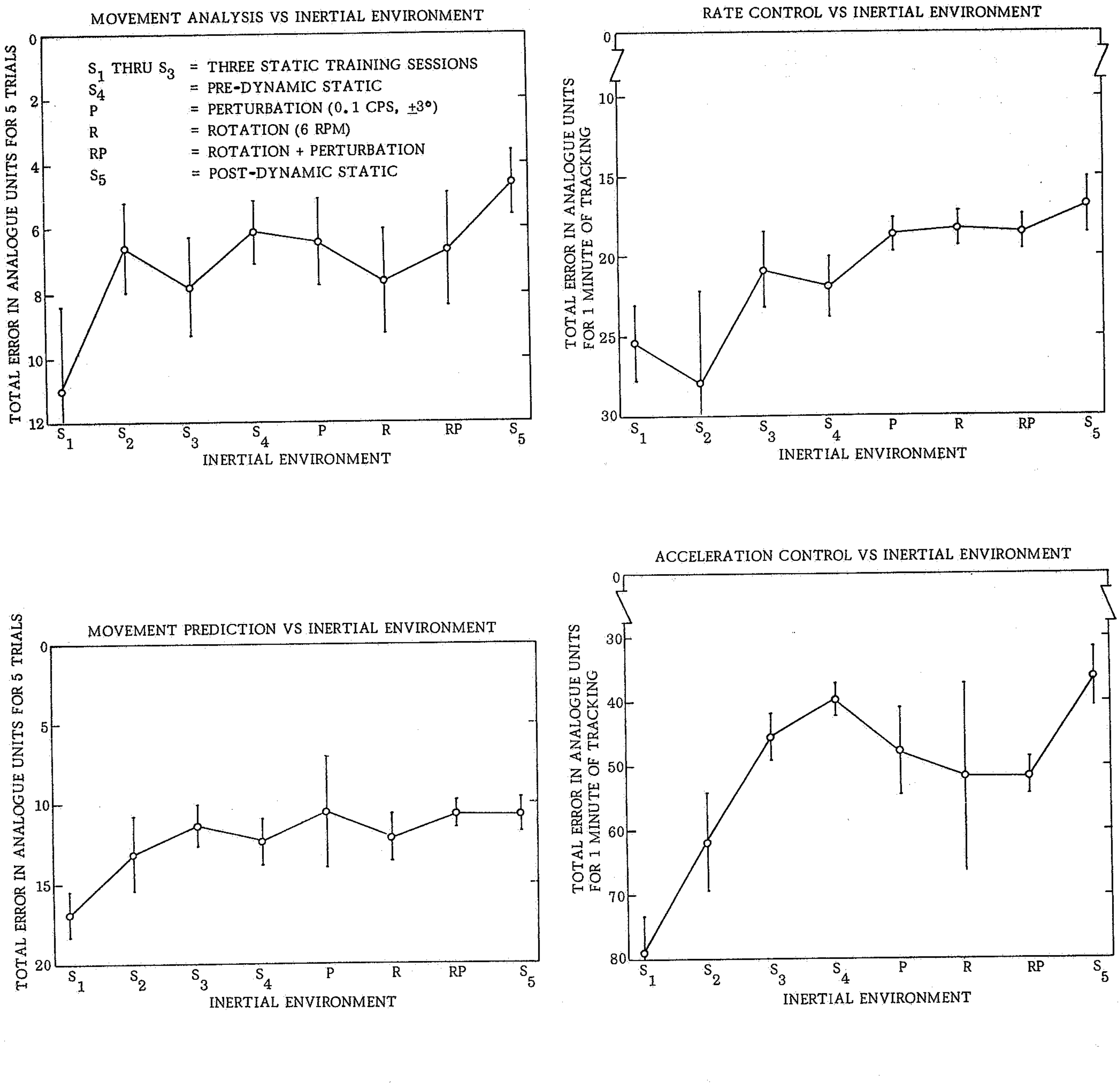


Figure 4-4. Systems Equalization ($\overline{X} \pm 1$ S. E. for N=12) Versus Inertial Environment

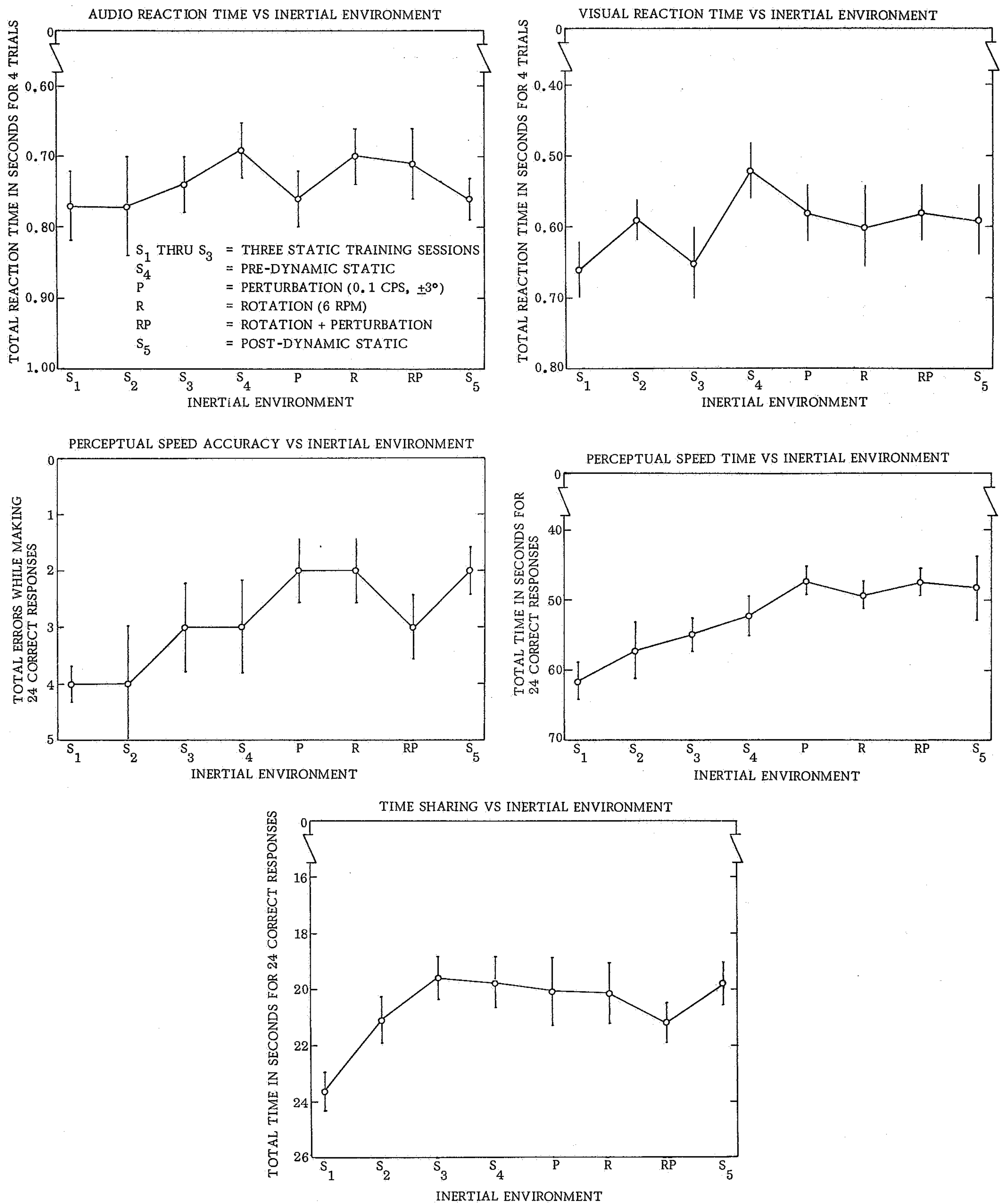


Figure 4-5. Perceptual-Cognitive ($\overline{X}$ ±1 S.E. for N=12) Versus Inertial Environment

d. Reaction Time Abilities: The slight relative decrement due to perturbation when the modality is aural (ART) could result from the unavoidable background noise during oscillation of the simulator when it is not rotating.

4.1.5.5 Mirror Tracing Abilities (Figure 4-6). These abilities suggest that the average subject maintained his mirror tracing speed (MTS) and accuracy (MTA) essentially unchanged regardless of the dynamic environment.

4.1.6 DISCUSSION. Because some learning was still evident in the more difficult tests at the end of the designated 4.5 hours of training, the better of the two static test scores (pre- and post-dynamic) was selected as the score of 100 per cent for normalization of the dynamic data. With the above precaution in mind, the results of an analysis of variance of the normalized data suggest:

(AHS)	Static over all three dynamic modes ($P < 0.01$)
(WFS)	Static over all three dynamic modes ($P < 0.05$)
(FD)	S over R and RP ($P < 0.05$)
(MD)	S over R ($P < 0.05$)
(SAM)	S over R and RP ($P < 0.05$)
(MA)	S over R ($P < 0.01$) and RP ($P < 0.05$)
(PST)	S over R ($P < 0.05$)
(TS)	S over RP ($P < 0.05$)
(VRT)	S over all ($P < 0.05$)
(ART)	S over P ($P < 0.01$)
(MTT)	S over P ($P < 0.01$)
(MTA)	S over RP ($P < 0.01$)

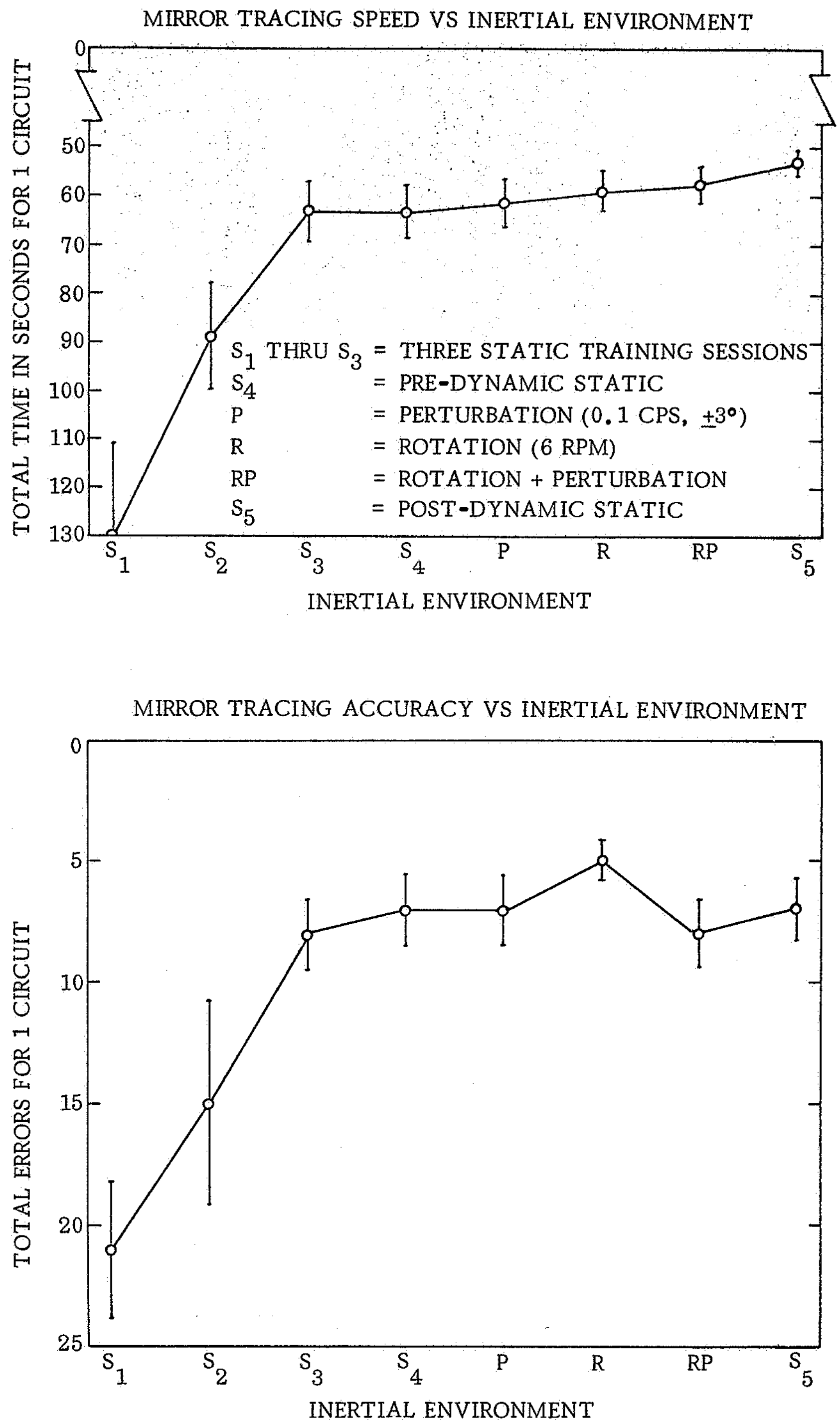


Figure 4-6. Mirror Tracing ($\overline{X}$ ±1 S.E. for N=12) Versus Inertial Environment

All other tests failed to demonstrate significant decrements from static scores.

The results in some cases show a significant change in score, but only in one test does decrement indicate that perturbation would be a hindrance to that type of operation. As might be expected, the task of maintaining a probe within a hole without touching the sides is difficult in the rocking environment. Such a task would still be possible if there were a contact between a fixture common to that being probed and the carpal portion of the hand. In administration of these tests there was little, if any, head motion so most vestibular stimulation resulted from passive motion of the subject by vehicle perturbation. Quite different results might be expected if a head motion were incorporated into the testing. Figures 4-7 and 4-8 indicate the relation between the tests as affected by the imposed variables and the significance of the differences in scores.

4.2 TASK II: EFFECT OF PERTURBATION ON PERFORMANCE FOLLOWING Y-AXIS HEAD TURNS DURING ROTATION

The previous study contract, NAS 9-5232, demonstrated a progressive performance decrement as the angle between the spin plane and the plane of the subject's head turn was increased. Task I of this study did not indicate that the passive movement of a subject during rotation, due to perturbation of the vehicle, would cause a significant problem. Those tests, however, restricted head motion to a minimum for the test being performed. Motion out of the spin plane was sinusoidal and, therefore, predictable in time and magnitude. Tasks requiring head turns in different planes impose cross-coupled stimuli on the semicircular canals that vary in magnitude and direction, dependent on subject orientation,vehicle rotation rate and motion due to the perturbation. The inertial field of such motion is complex and changing and it is unlikely that prediction would be possible. Rapid habituation would most likely result only from non-specific suppression of the vestibular signal.

4.2.1 PURPOSE OF THE STUDY. The purpose of the Task II study was to assess the importance of subject orientation on performance within an inertial force field that was being perturbated.

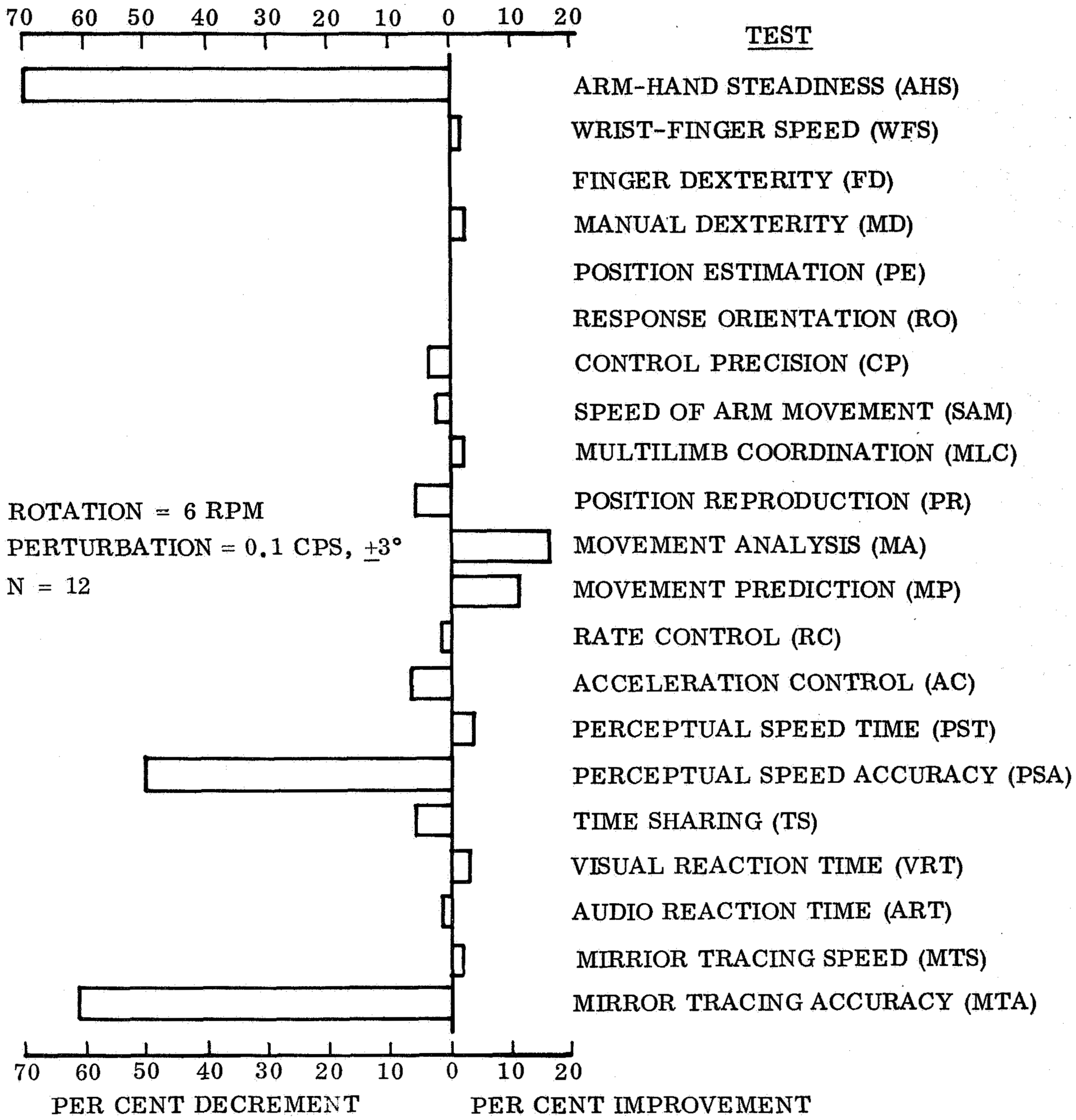


Figure 4-7. Per Cent Change in Perrotatory Performance with Perturbation

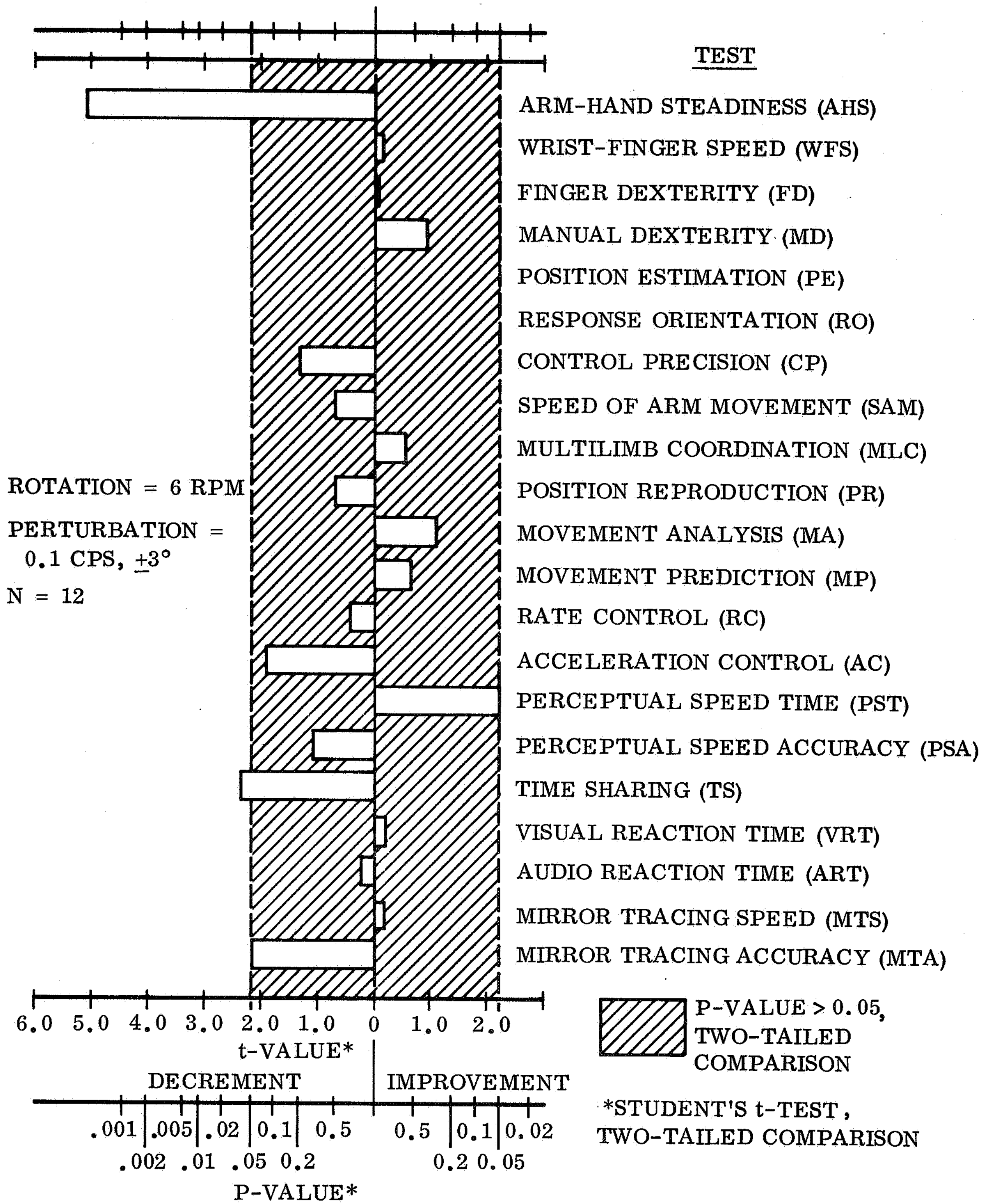


Figure 4-8. Significance of Change in Perrotatory Performance with Perturbation

4.2.2 METHOD. The same test arrangement (described in Appendix C) was used for this study as in the previous contract. Recording techniques, however, were extended. In addition to the eye motion camera (EMC) and vertical and horizontal electro-oculograms, a vectoroculogram (VOG) was made. This is an integration of the horizontal and vertical electro-oculograms (EOG) and provides a light spot on the cathode ray tube (CRT) that represents the point of visual fixation. The eye-camera technique is not appropriate for space use, but if visual fixation time could be determined by the VOG, it would be an appropriate test for the determination of habituation in a rotating space vehicle. The RATER test as previously reported[11] was used and the head turn recording, EOG, EMC, frame number, and VOG were "stacked" and recorded on a video tape recorder. This allows simultaneous data presentation for analysis. This system is described in Appendix D.

Only Y head turns were made. This limited the anticipated severity of semicircular canal stimulation and reduced the testing per subject so it could be accomplished in one day.

The primary goal of this study was to acquire information on the effect of perturbation on the process of adjustment to rotation. A secondary purpose was to investigate the use of the vectoroculograph (VOG) as a practical substitute for the eye-motion camera for recording eye movement.

4.2.3 PROCEDURE. Experiment procedures are discussed in the following paragraphs.

4.2.3.1 Subjects. The test sample consisted of twelve volunteers from San Diego colleges. They were males of 22 ±2 years, 167 ±23 pounds and 69 ±4 inches in height. An additional six subjects of comparable background and vital statistics began testing but did not finish the required regimen, three because of instrumentation malfunctions and the remaining three because they found the most stressful orientations physiologically disturbing. Before being exposed to the environment of the dynamic test simulator, the subjects were required to pass an airman's third class medical examination. None of the subjects had histories of undue susceptibility to motion sickness. No special instructions were given to the subjects regarding diet or rest preceding their day of experimental performance.

4.2.3.2 Apparatus. The simulator, subject restraints, data pickups at the subject and performance tester were unchanged from the previous contract (described in Appendix C). Rotation of the subject was achieved using the Manned Revolving Space Station Simulator (MRSSS) shown in Appendix A. Orientation and restraint were achieved using the 45-degree chair and its associated head restraint. With the centrifuge rotating at 12.2 RPM to produce one radial g at the restraint chair position (centrally located within the MRSSS at 20 feet from the centrifuge spin axis), the gravitocentrifugal resultant was perpendicular to the MRSSS floor when the simulator was tilted at 45 degrees. The 45-degree tilt combined with the 45-degree angle of the restraint chair tilting the subject on his left side permitted, as in the previous contract, orientations of the subject for Y-axis head turns at 0, 45 and 90-degree interplanar angles to the centrifuge spin plane by simply rotating the chair, as seen in Figure 4-9. The Westgate Laboratories EMC-2F eye-motion camera was again used to record direction of gaze, the camera being fixed to the subject by the head restraint and dental bite bar as shown in Figure 4-10. The Response Analysis Tester (RATER), shown in Figure 4-11, was used as the perceptual-motor performance device with the display collimated to one degree of visual angle. The RATER tests correct rote responses to lights of four different colors (red, yellow, green, and blue) that are presented in an infinitely random order. The subject depresses one of four console buttons that corresponds to each color; when the correct button is pressed, the next color appears. Total responses and correct responses are recorded automatically. The RATER also produces a d-c signal that corresponds to the subject's latency in responding to each color displayed. The RATER response latency was recorded on the polygraph strip chart. Essential changes in apparatus from the previous contract were made to incorporate the vector-oculograph (VOG) system into the study for additional data recording. The subject's d-c EOG signals were amplified by Kintel 114A amplifiers in the MRSSS before being transmitted through the centrifuge slip-rings to the main test control room. In the control room the EOG signals were simultaneously recorded by two systems. The individual horizontal and vertical EOG's were written out by two channels of a Sanborn 150 polygraph on the same chart recording the subject's and on-board examiner's ECGs,

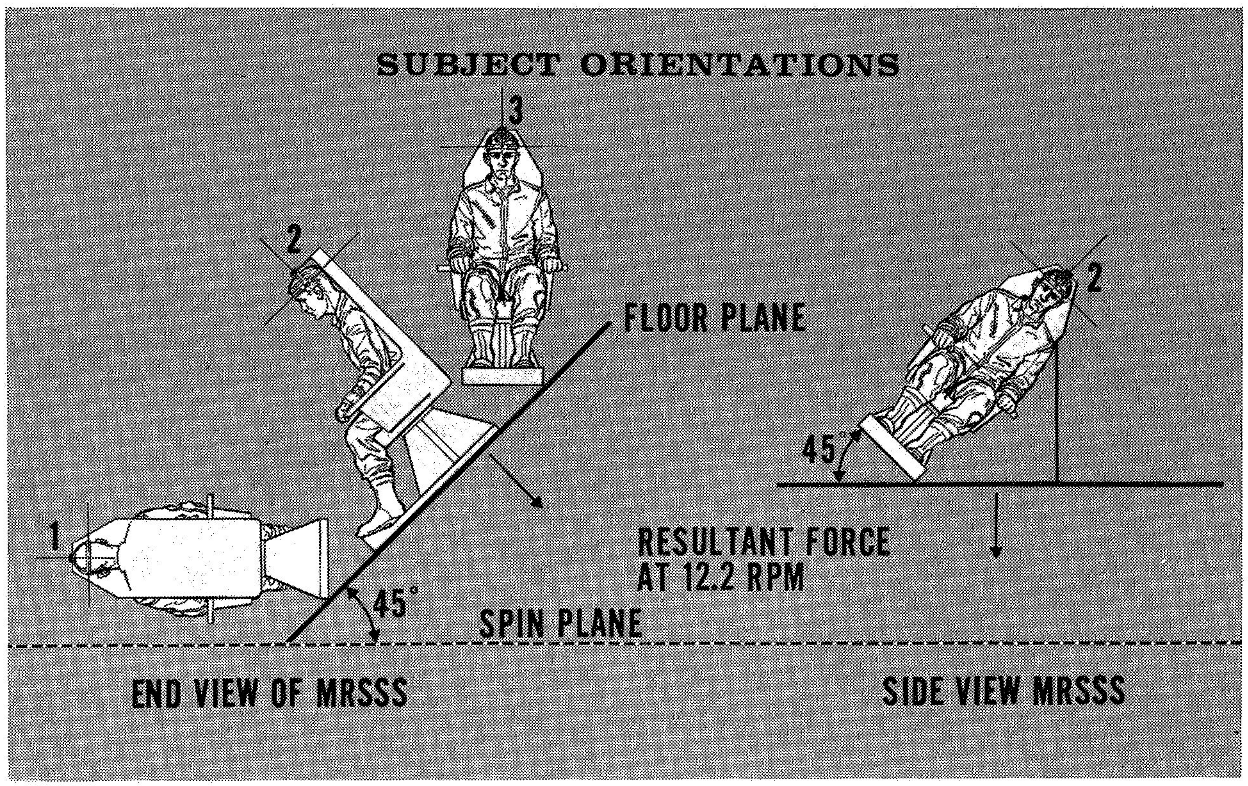


Figure 4-9. Subject Orientations

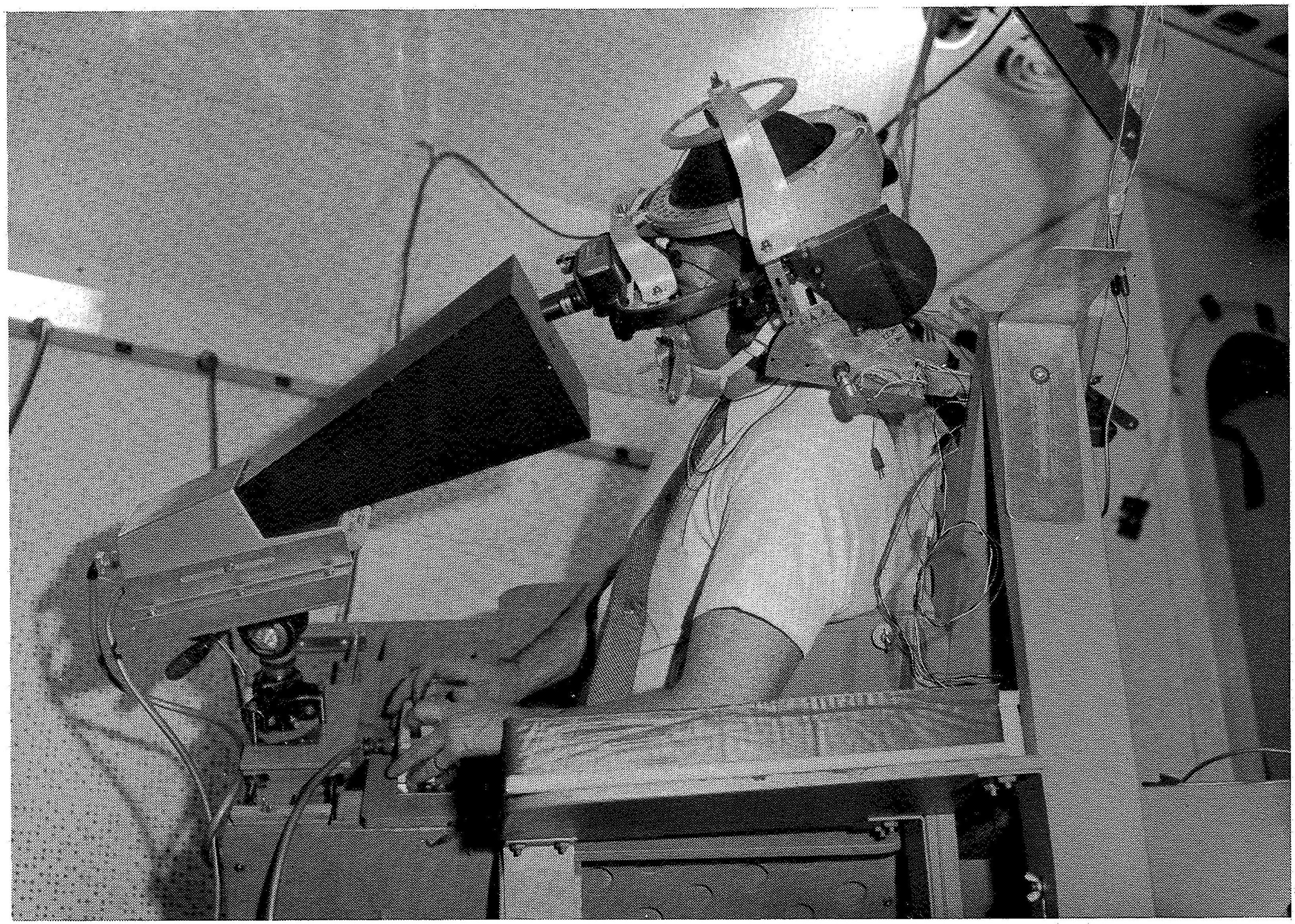


Figure 4-10. Camera Fixed by Head Restraint and Dental Bite Bar

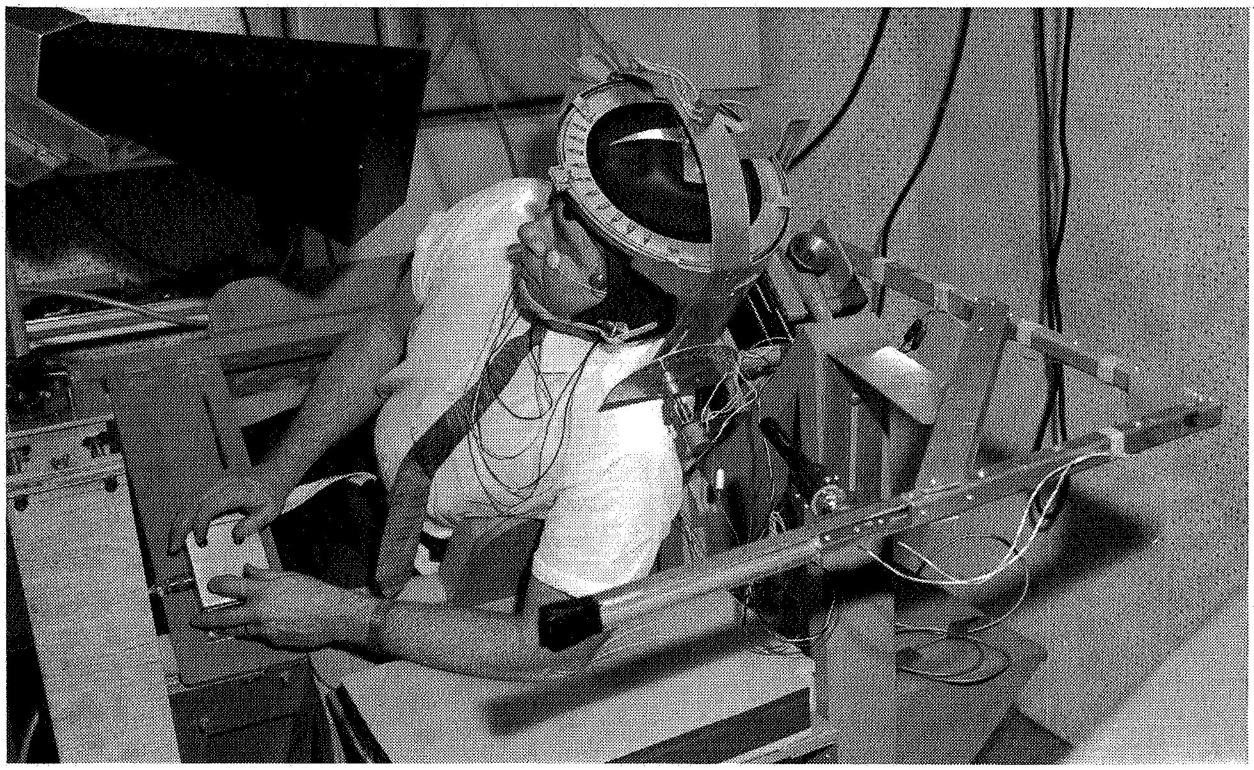


Figure 4-11. Subject in the Inclined Chair

the RATER response latency, the testing event marker, and the head-turn rate. The horizontal and vertical EOG signals were also paralleled to the VOG system. For this system the two EOG signals were combined by a Tektronix 503 dual-beam oscilloscope into a single two-dimensional eye-movement vector. To provide an integrated display for data records, three readouts (polygraph EOGs, oscilloscope VOG and a digital count of the eye-motion camera frame number) were individually photographed by separate TV cameras and synchronized into a single picture by a special effects generator for video taping and/or subsequent kinescoping. A more detailed description of the VOG and a schematic diagram of the system are included in Appendix D.

4.2.3.3 Experiment Design. As in the previous contractual study, the subject's task was to perform a testing sequence in each of the combinations of head turn orientation and force field variation. Each sequence consisted of ten 15-second trials separated by 20-second waiting periods at the cue light position. All head turns were restricted about the subject's Y cranial axis by the head constraint. The subject would wait for the cue light with his head dorsoflexed 35 degrees back from the horizontal. The automatic timing system turned on the cue light and RATER display, and started the EMC simultaneously. The subject immediately turned his head 70 degrees downward as rapidly as possible and began responding to the RATER display by pressing the appropriate buttons. At the end of the 15-second scoring period, the timer would shut off the RATER display, which was the subject's signal to turn his head back to the cue light position and to wait for the light to flash on at the end of the 20-second waiting period. At the end of the ten-trial sequence (150 seconds of scoring), the eye-motion camera film was changed and the subject reoriented by rotating the restraint chair relative to the centrifuge spin axis.

Each of the subjects was instructed to perform as well as possible during the 150-second (ten-trial) sequence in each orientation. The subjects were tested in the same six modes: two each with the head turn plane at 0, 45 and 90 degrees to the MRSSS spin plane, once with the simulator rotating at 12.2 RPM without perturbation, and once with it rotating at 12.2 RPM and perturbating about a tangential axis at ±3 degrees and at a rate of 0.1 cps. Permutations of the six testing modes were selected on a basis of balance and randomly assigned to the twelve subjects. The subject numbers and their assigned orders of testing sequences are tabulated below.

Orders of Test Sequences

1	S 0°-45°-90°	P 0°-45°-90°
2	P 0°-45°-90°	S 0°-45°-90°
3	S90°-45°- 0°	P90°-45°- 0°
4	P90°-45°- 0°	S90°-45°- 0°
5	S45°- 0°-90°	P45°- 0°-90°
6	P45°- 0°-90°	S45°- 0°-90°
7	S90°- 0°-45°	P90°- 0°-45°
8	P90°- 0°-45°	S90°- 0°-45°
9	S45°-90°- 0°	P45°-90°- 0°
10	P45°-90°- 0°	S45°-90°- 0°
11	S 0°-90°-45°	P 0°-90°-45°
12	P 0°-90°-45°	S 0°-90°-45°
	S = 12.2 RPM	P = 12.2 RPM and ±3° @ 0.1 cps

4.2.4 RESULTS. Of the eighteen subjects who began testing, twelve performed at all six modes and were grouped within a single sample for data reduction and interpretation. For these twelve subjects, two categories of response were considered: (a) the net RATER score (total correct responses minus total incorrect responses) for the 150 seconds of scoring during each modal sequence and for each of the ten trials making up a sequence, and (b) the parameters of reaction linking the starting signal to the first correct RATER response: the latent period to beginning of head turn, the head turn, end of head turn to eye fixation and from eye fixation to first correct RATER response.

Figure 4-12 graphs the mean net RATER score for all twelve subjects for each of the ten 15-second trials in each of the testing modes. The graph indicates that for most trials there is a decrement in mean scores as the interplanar angle increases, and for all interplanar angles there tends to be a reduced performance when perturbation is added to rotation. The exceptions to the latter are the last four trials of the Y_{90} sequences where there is a mean score decrement without perturbation when compared with the situation of combined dynamics.

Figure 4-13 shows the mean net RATER score for the full sequence as a function of interplanar orientation for each of the dynamic modes. This figure makes the two observations mentioned above more apparent. A decrement of performance is seen as the interplanar angle increases. This decrement is increased with perturbation but becomes obscured during the most stressful interplanar orientation by the cross coupling at Y_{90}.

To test the statistical significance of the data presented in Figure 4-13, each subject's data was normalized on the basis of 100 percent performance value for his best sequence score. Overall means for the total sample then gave performance percentages ranging from 96 percent for Y_0 (R only) to 80 percent for Y_{90} (RP). An analysis of variance was performed on the normalized data using a P-value equal to or less than 0.05 as being significant. Comparing sequences with one another, only Y_{90} (R) and Y_{90} (RP) demonstrated a significant degradation in performance and only when compared to Y_0 (R). Not included on this graph were the results of perturbation-only sequences run by the last six of the twelve subjects. Each of these subjects ran a pre-rotation and post-rotation perturbation sequence, three subjects with the restraint chair facing tangent to the plane of spin (the orientation for Y_0 and Y_{90} sequences) and three with the chair facing radially (the orientation for Y_{45} sequences). Their scores for these sequences did not differ significantly from their Y_0 performance. Table 4-1 lists the mean scores achieved by each group of three subjects in their perturbation-only sequences.

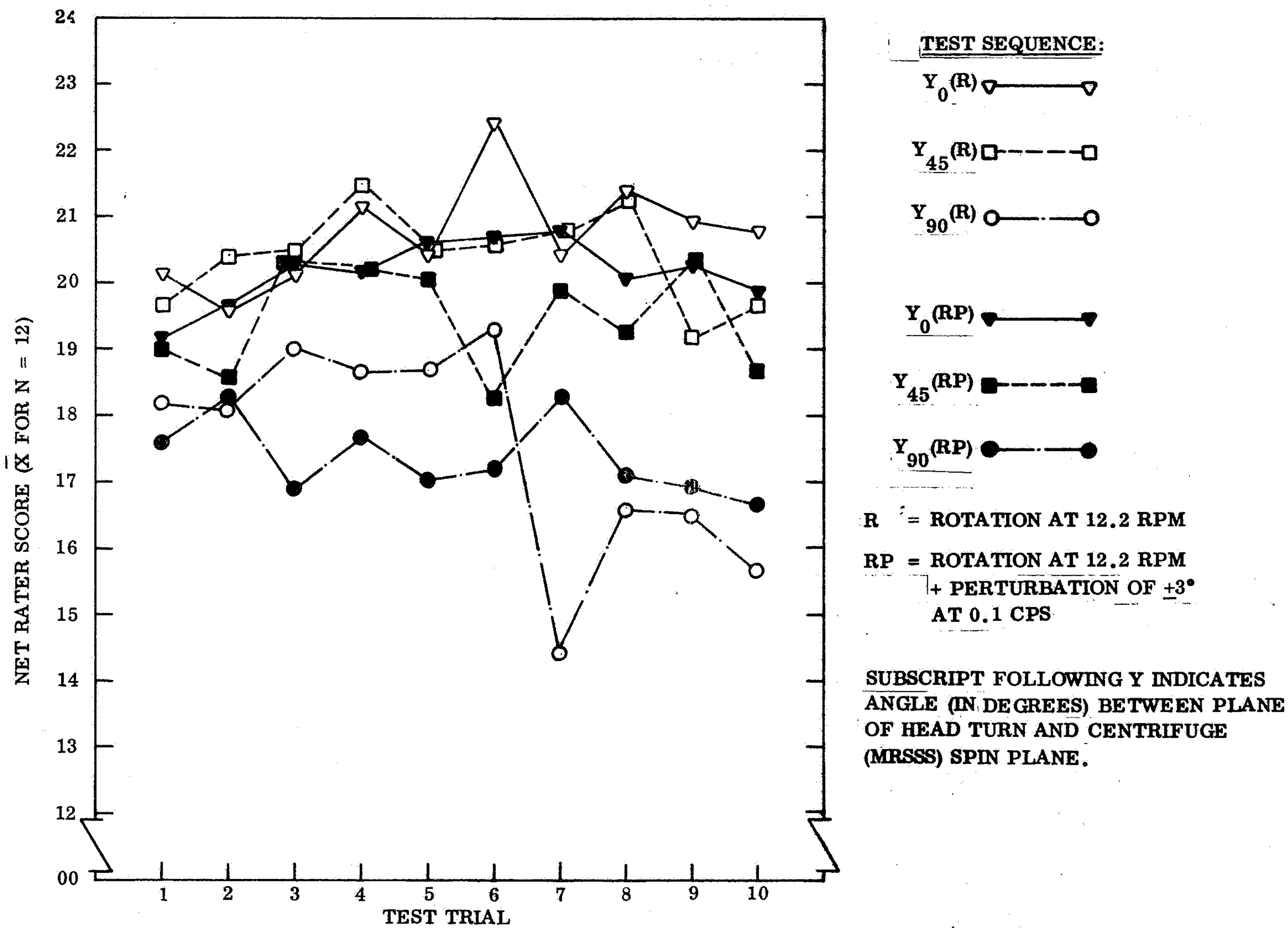


Figure 4-12. Net RATER Score vs Test Trial

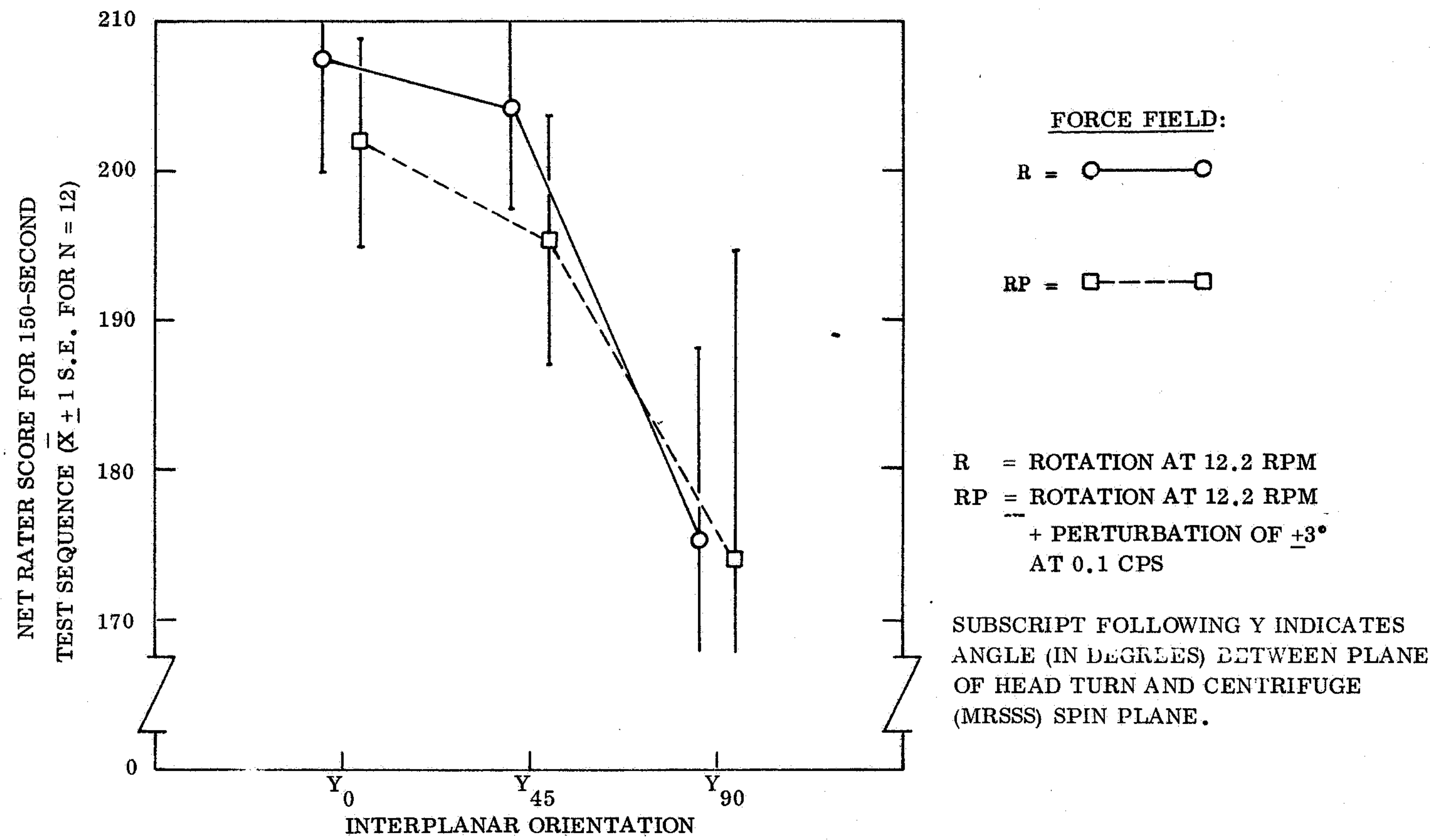


Figure 4-13. RATER Score vs Subject Orientation

Table 4-1. RATER Score Versus Perturbation Only

Sequence	$\bar{x}$	N
Pre-spin P_{45}	208	3
Post-spin P_{45}	207	3
Pre-spin P_0	212	3
Post-spin P_0	207	3

$\bar{x}$ = mean RATER score for three subjects for 150-second sequence.

N = sample number

P_{45} = subject facing radially

P_0 = subject facing tangentially.

Figure 4-14 graphs initial subject performance dynamics as a function of the six modal test sequences. Intervals are in seconds of real time for means of the entire sample. Though these mean values show a progressive increase in time from starting signal to first correct RATER response, an analysis of variance of the data did not show these changes to be significant.

Data presented in Figure 4-14 was reduced from the polygraph strip chart, the VOG tapes and the EMC films. Appendix D details the methods used to extract the VOG and EMC data. In comparing the VOG and EMC eye motion loci for various trials it was found that they gave identical measurements of eye movement and could be used interchangeably from that standpoint.

Figures 4-15 and 4-16 compare, respectively, oculograms for the same test trial plotted, respectively, from VOG and EMC film. The numbers in both oculograms refer to the EMC frame numbers from the cue light start signal. The EMC was run at 8 frames/second. The VOG tape originally records 60 fields (frames)/second and when kinescoped provides a permanent record of 24 frames/second. A comparison of Figures 4-15 and 4-16 indicates the major difference between the EMC and VOG data, that being that the EMC fixes gaze position in the field of regard independent of head position,

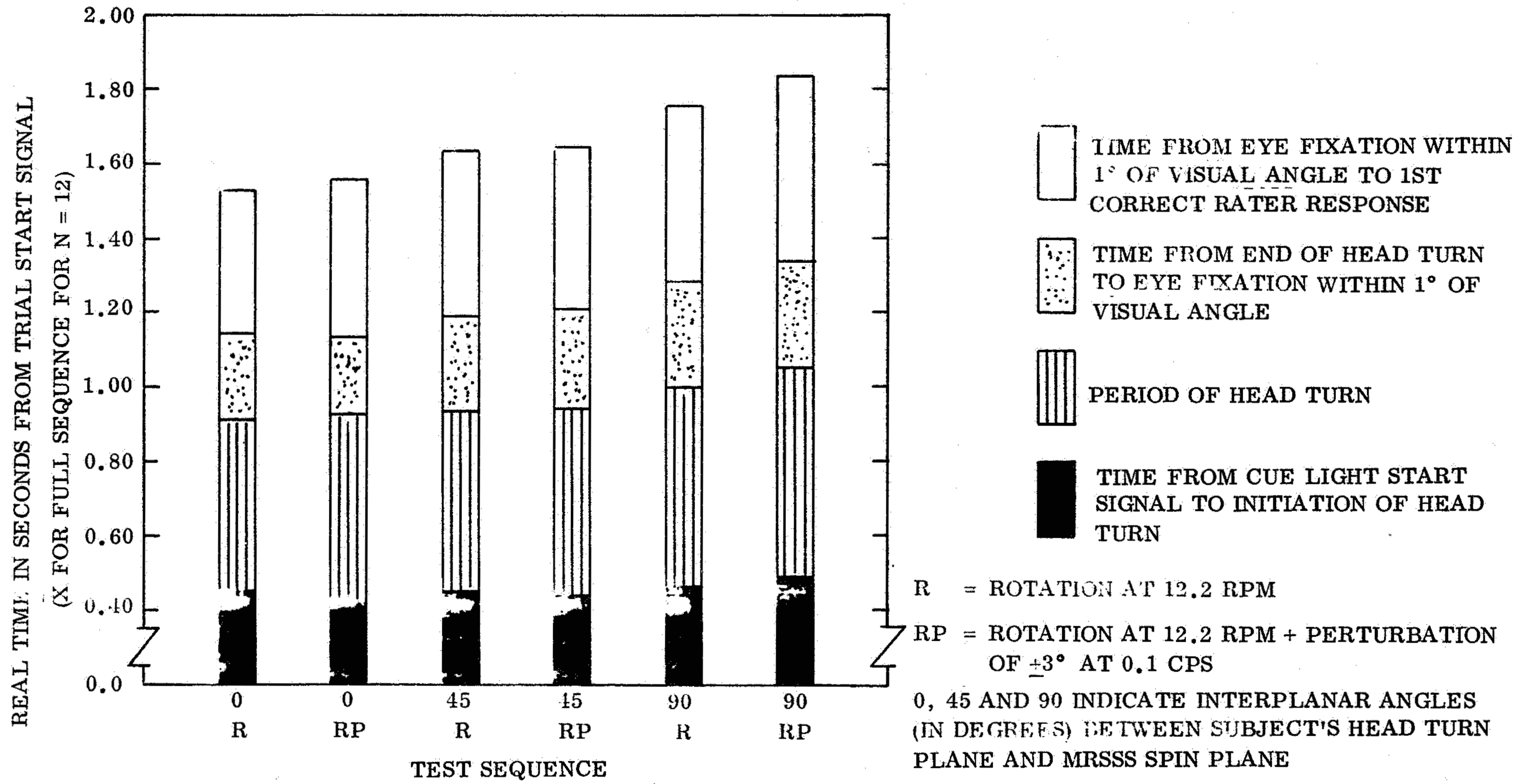
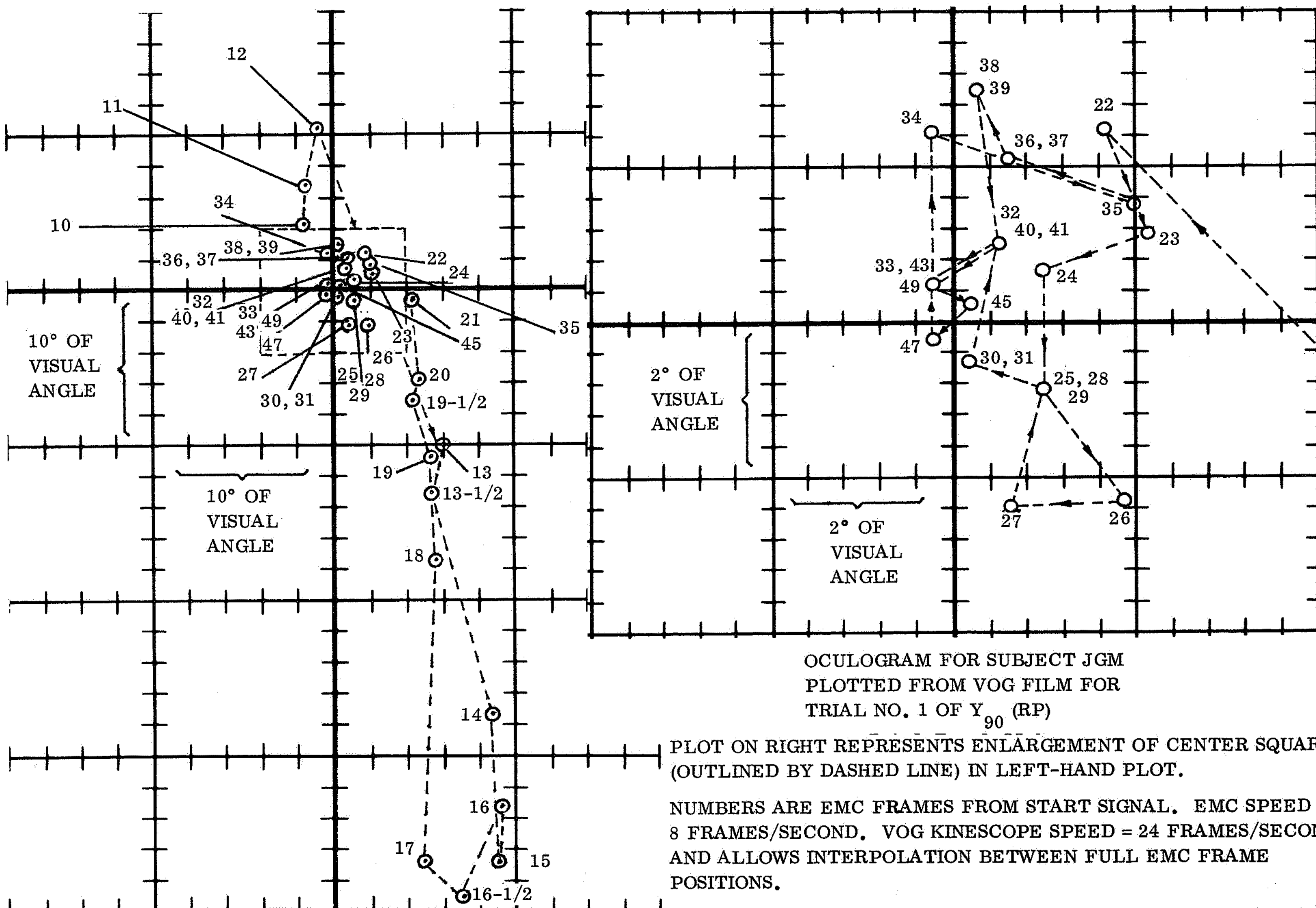


Figure 4-14. Subject Response vs Test Sequence



OCULOGRAM FOR SUBJECT JGM PLOTTED FROM VOG FILM FOR TRIAL NO. 1 OF Y_{90} (RP)

PLOT ON RIGHT REPRESENTS ENLARGEMENT OF CENTER SQUARE (OUTLINED BY DASHED LINE) IN LEFT-HAND PLOT.

NUMBERS ARE EMC FRAMES FROM START SIGNAL. EMC SPEED = 8 FRAMES/SECOND. VOG KINESCOPE SPEED = 24 FRAMES/SECOND AND ALLOWS INTERPOLATION BETWEEN FULL EMC FRAME POSITIONS.

ALL PLOTTED CIRCLES REPRESENT GAZE POSITIONS RELATIVE TO THE SKULL.

Figure 4-15. Vector Oculogram for Subject JGM

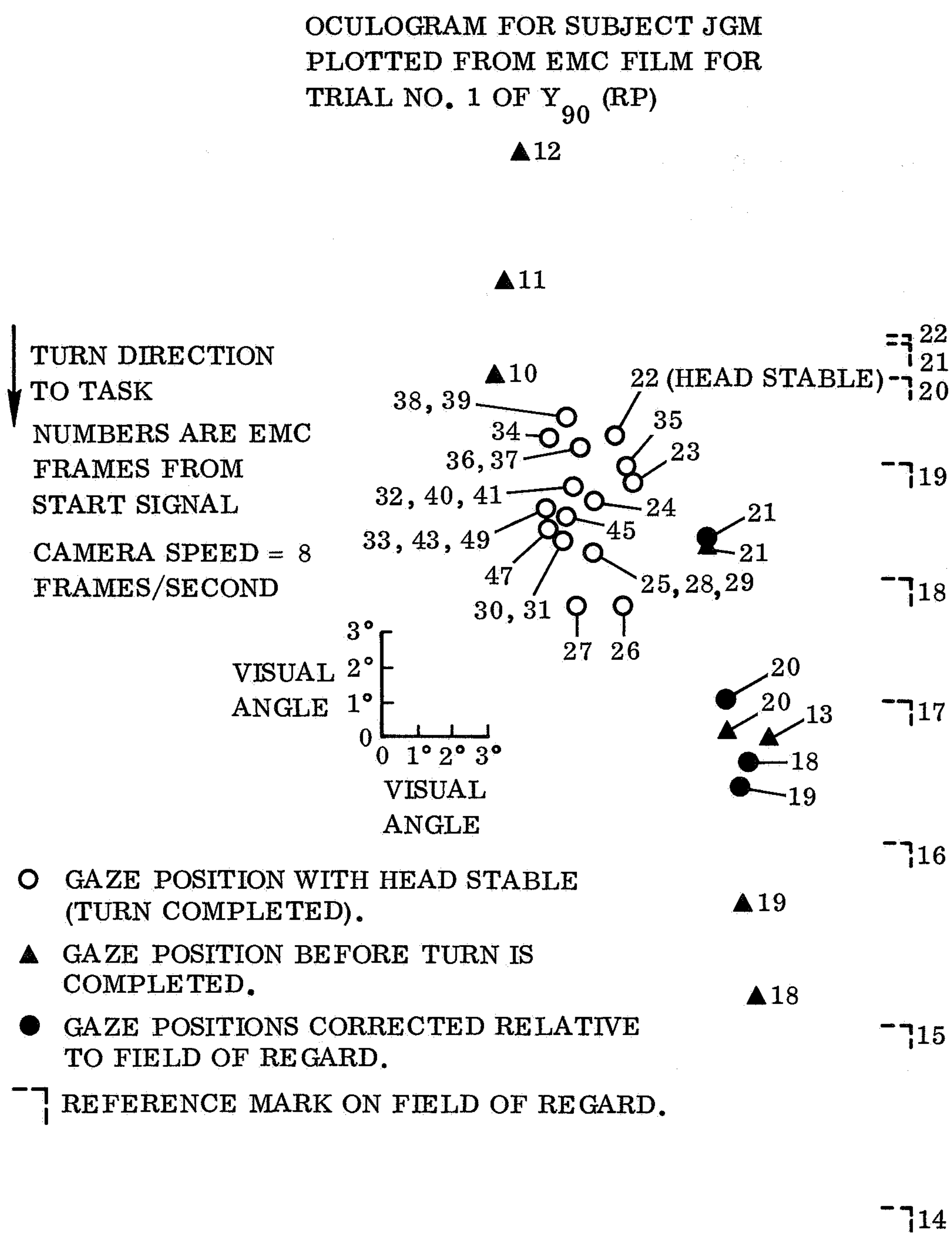


Figure 4-16. Eye Motion Camera Oculogram for Subject JGM

while the VOG indicates only gaze position relative to the head. In Figure 4-15, prior to frame 22, when the head becomes stable at the end of head turn, gaze positions 18 thru 21 could be repositioned relative to the changing field of regard by correcting relative to a reference mark in that field. Positions 10 thru 13 could not be so corrected as the reference mark was not yet in view on film. Subsequent to point 49, all gaze positions lay in the area circumscribed by 45 thru 49, and therefore were not plotted. Comparing the two plots it would seem that for tests involving head immobility the VOG provides an adequate substitute for the EMC.

4.2.5 DISCUSSION. This study was the third experimental effort performed by this laboratory involving Y-axis head turns and their effect on perceptual-motor performance. The first study (Task I of NAS 9-5232) used the Logical Inference Tester (LOGIT) as the performance tester, while the second study (Task II of NAS 9-5232) used the RATER as in this study. The first two studies exposed the subjects to Z-axis (side-to-side) head-turn sequences while this study exposed them to Y-axis head-turn sequences with perturbation added to rotation. Apart from that, the formats were quite similar and the Y-axis sequences with rotation and no perturbation are capable of comparison.

By comparison, the results of this present study are consistent with the first two. The first experiment (Task I of NAS 9-5232) demonstrated a 6 percent degradation in LOGIT performance for Y_{45} and a 12 percent degradation for Y_{90}. The second study (Task II of NAS 9-5232) demonstrated a 10 percent degradation in RATER performance for Y_{45} and a 25 percent degradation for Y_{90}. This present study demonstrated a 2 percent degradation in RATER performance for Y_{45} and a 16 percent degradation for Y_{90}. The greater degradation witnessed in the first RATER study must in part be due to the test regimen including Z-axis head-turn sequences, which have been shown to be significantly more degrading than Y-axis turns of comparable interplanar angle. In the first RATER study, the Z_{45} and Z_{90} sequences produced 25 percent and 37 percent performance degradation, respectively. In that study, as in the present one, permutations of the various stress modalities were balanced, but this only serves to balance the cumulative stress effects among all sequences, not nulling out such effects.

Again, comparing these three studies, it is seen that the head turn times are quite similar in magnitude as well as proportion. Though the eye-fixation times in the second study (Task II of NAS 9-5232) are significantly longer than those seen in the present study, this would be anticipated in view of the substantially greater degradation in performance and in part must be due to the exposure to Z-axis head turns as part of the test regimen.

In the present study, though perturbation did not produce a significant change in performance, consideration of the mean performance values as a function of perturbation allows some suggestion of possible effect. Table 4-1 indicated that perturbation alone did not have a degrading effect on performance; therefore, the relative decrement in mean performance values for Y_0 (RP) and Y_{45} (RP) compared to the comparable (R) sequences could result from labyrinthine cross-coupled accelerations due to the passive sinusoidal tilting of the subject relative to the MRSSS spin plane. As it is a sinusoidal tilting it would be anticipated that the effect might be marginal since the resultant stimulus to the cupula-endolymph system would reverse in direction every five seconds. When considering the more traumatic Y_{90} orientation, however, it appears that the minor degradation due to perturbation no longer manifests itself within the context of the major degradation resulting from cross-coupling due to active head turns. This appears to be especially true in the latter trials of the sequence when the cumulation of stress is causing the most significant performance decay.

In conclusion, it has been demonstrated that perturbation imposed in this experiment does not have significant effect on perceptual-motor performance, either with or without simultaneous rotation. It has also been demonstrated that the VOG is a satisfactory substitute for the EMC in recording two-dimensional eye movements relative to the skull. It is seen, also, that the test results are consistent with previous studies performed of similar format.

4.3 TASK III: OCULOGYRAL ILLUSION EXTINCTION IN STABLE AND PERTURBATING ENVIRONMENTS.

It has been noted in this and other laboratories [5, 16, 17] that a suppression (adaptation or habituation) of ocular, perceptual, and somatic responses to Coriolis vestibular stimuli occurs in a rapid and predictable manner when repeated, and that the suppression observed is closely specific for the stimulation being used. The transfer of the suppression to other forms of vestibular stimuli, including the unpracticed quadrants of identical Coriolis vestibular stimuli, has not been significant. During combined rotation and perturbation exposures of subjects and examiners in the Convair MRSSS, impressions of altered vestibular suppression rates have been consistently reported that indicate the perturbating environment is more easily tolerated. Task III provides statistical comparison of rate and transference of vestibular suppression of the oculogyral illusion resulting from cross-coupled angular acceleration as a function of the presence or absence of perturbation. Perturbation presents a unique stimulus modality in that it provides passive rotation of the subject's labyrinths relative to the spin plane of the simulator, but in a form that involves a minimum of conscious involvement. It may thus provide some evidence as to what aspects of the stimulus framework, from the consciousness standpoint, are of primary importance in establishing endorgan signal suppression.

4.3.1 PURPOSE OF THE STUDY. The purpose of the Task III study was to compare the vestibular suppression due to head rotations in a rotating environment with that due to head rotations in an environment that is simultaneously rotating and perturbating.

4.3.2 METHOD. To maximize the use of available centrifuge time and to provide information on the rate of response extinction, Task III was divided into parts A and B; the subjects involved in part A were re-exposed one month later in part B.

Task III consisted of exposing subjects to four hours of rotation, with or without perturbation. Prior to and subsequent to the dynamic exposures, subjects received vestibular caloric tests, first one ear and then the other. During the dynamic exposures in the simulator the subjects made X-axis head turns, toward one shoulder only, at 15-minute intervals. Responses to both rotational and caloric vestibular stimuli were measured by durations of resultant oculogyral illusions.

As it is of great importance that responses both to the rotational and caloric stimuli be of sufficient initial magnitude to permit measurable decrement or suppression of response, subjects and stimuli were chosen to ensure such adequacy. Head turns were 45 degrees about the X axis at maximum rate, with the simulator angular velocity at 8 RPM (6 RPM was found to be insufficient for consistent response). Caloric stimulation consisted of 50 cc of 25°C water delivered at a rate of 1 cc/second against the posterior superior wall of the external auditory canal, with the head positioned to place the lateral canals in a vertical position. Only subjects with normal audiometric profiles for the 20-30 age span and with active caloric responses were used in Task III. A lead time of two days was provided for certification of subjects for use in the study. The bite bar arrangement that was used to limit the extent of head turn and to ensure that the motion was made in a consistent plane is shown in Figure 4-17.

After all had received their caloric stimulations, subjects were seated facing the leading bulkhead of the MRSSS (upon which the OGI target light is affixed) and the MRSSS was spun-up to 8 RPM.

Subjects were given a stopwatch and positioned with the restraining bite bar clenched between their teeth. The ambient illumination was extinguished prior to each head turn (the OGI target consisted of a three-inch wire cube painted with fluorescent paint and illuminated by a 40-watt UV fixture; no light was visible). The on-board examiner commanded "one, two, three, TURN". At the command "TURN", the subject turned his head as rapidly as possible to the right. The bite bar restraint maintained the turn in the frontal plane and prevented the turn from passing beyond the designated 45 degrees. The subject started his stopwatch at the same time he began his headturn and stopped it when the resultant OGI appeared to have terminated. He did his best to remember the direction (clock hour numbers) and magnitude (units equal to target light side dimension) of the illusory movement of the target for subsequent recording

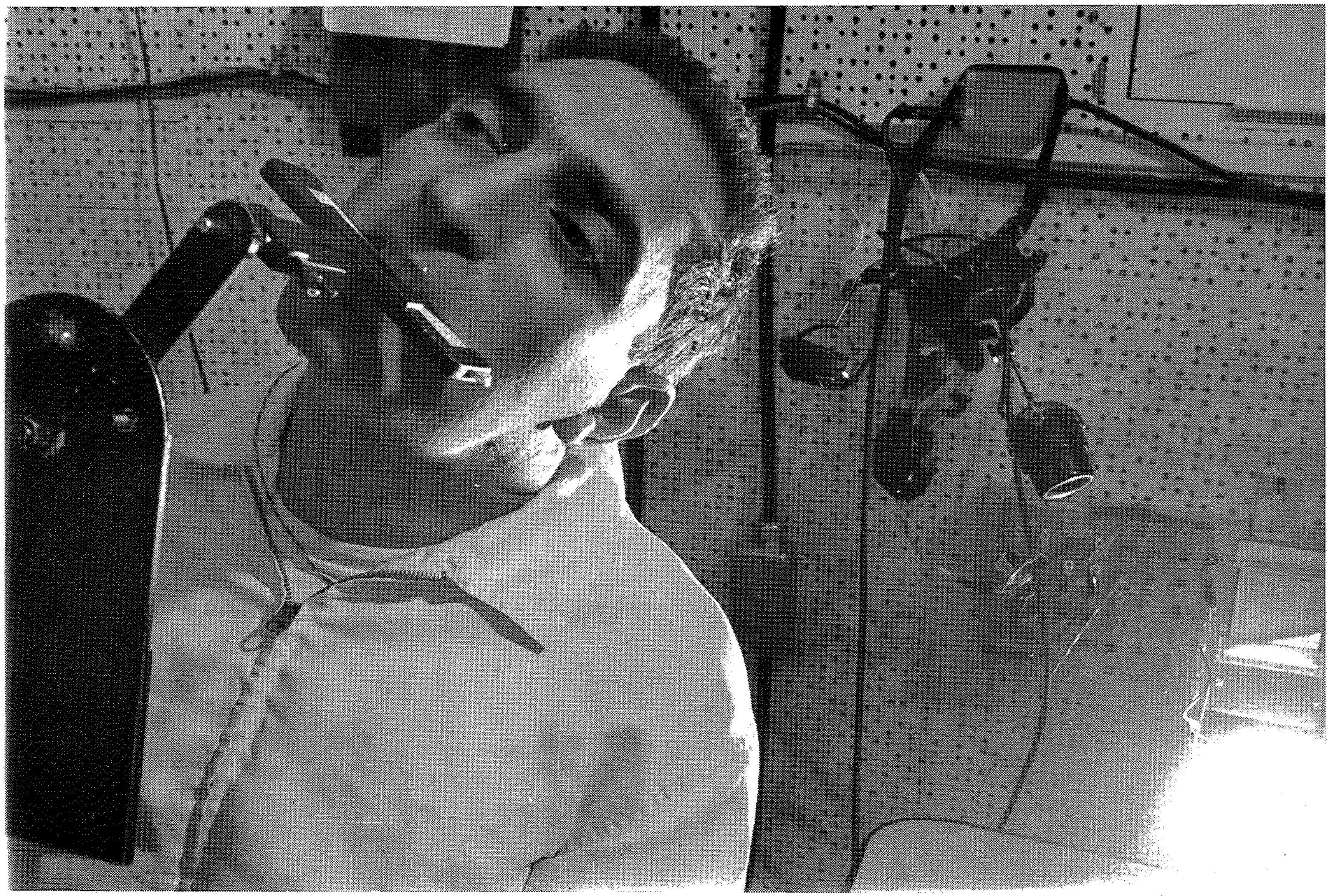


Figure 4-17. Bite Bar Restraint Used to Limit Head Turn Motion

on paper. This requirement for memory of illusion was meant to provide a mental task to maintain central arousal of the subject for consistency of that aspect of response threshold.

Subjects were instructed to spend an estimated one minute (at a consistent turning rate) to return slowly back to center stop. Two minutes after the initial "TURN" signal the room lights were turned on, the times recorded, and the stopwatch and polygraph connections transferred to subjects 3 and 4. The testing procedure followed for subjects 1 and 2 was repeated for subjects 3 and 4, followed by a repetition of the complete testing cycle for all four subjects every fifteen minutes of the four hours of dynamic exposure. Just prior to "spin down" a response to the unexperienced head-turn direction was made.

At the end of the four hours of dynamic exposure the subjects received caloric stimulations as during the pre-spin portion of the test, after which they were released.

Half of the sample (8 subjects) were exposed to rotation plus perturbation (±3 degrees, 0.1 cps) during part A and the other half during part B. Half the subjects received caloric irrigations in their left ear first, the other half in their right ear first, this initial order being maintained throughout both parts of the Task (A and B). Subject numbers were assigned in groups of fours on a random basis as shown in Table 4-2.

4.3.3 RESULTS. Twenty subjects were exposed to the first part of the test program. The first four were exposed to 6 RPM and it was found that the magnitude of oculogyral illusion (OGI) produced on the first head turn was not great enough to satisfactorily demonstrate progressive habituation during the four hours of exposure. The remaining sixteen subjects were exposed to 8 RPM; at that velocity a good OGI response was observed. One subject had a vegetative response as a result of repeated head tilts and his testing was suspended to avoid possible nausea which would have required the abort of all four test subjects. Eleven of the remaining subjects returned for the second part of testing.

Table 4-2. Schedule For Task III

Dynamic Exposure / Caloric Testing	PART A: R* PART B: R + P**	PART A: R + P PART B: R
(1) Left Ear (2) Right Ear	Ss 1 thru 4	Ss 5 thru 8
(1) Right Ear (2) Left Ear	Ss 9 thru 12	Ss 13 thru 16***

*R = rotation (8 RPM)
**P = perturbation (±3°, 0.1 cps)
***Ss 17-20 provided backup for data loss.

Estimated Subject Time:* 0900-1000: 1 hr. pre-dynamic
1000-1400: 4 hr. dynamic
1400-1500: 1 hr. post-dynamic

Figure 4-18 shows the results for all subjects tested. From the slope of the regression curves there is no apparent difference in the rate of adaptation. There is a difference in extent of habituation; this, however, could be due to the sample size difference. Figure 4-19 is for the eleven subjects who were tested in both parts A and B. The difference in habituation achieved in the two groups has an even greater significance (points are the mean ± one standard error) when the subjects who did not return for the second test are deleted, but the rate of extinction appears the same.

4.3.4 DISCUSSION. It was hypothesized that habituation during rotation with perturbation would take place faster than in the stable situation. This was based on the supposition that the greater the interaction of a subject with the cross-coupled accelerations, the faster the various stimuli would be suppressed centrally. It is clear that the data show a reversed situation. The OGI was extinguished at about the same rate but to a significantly lesser degree than without perturbation.

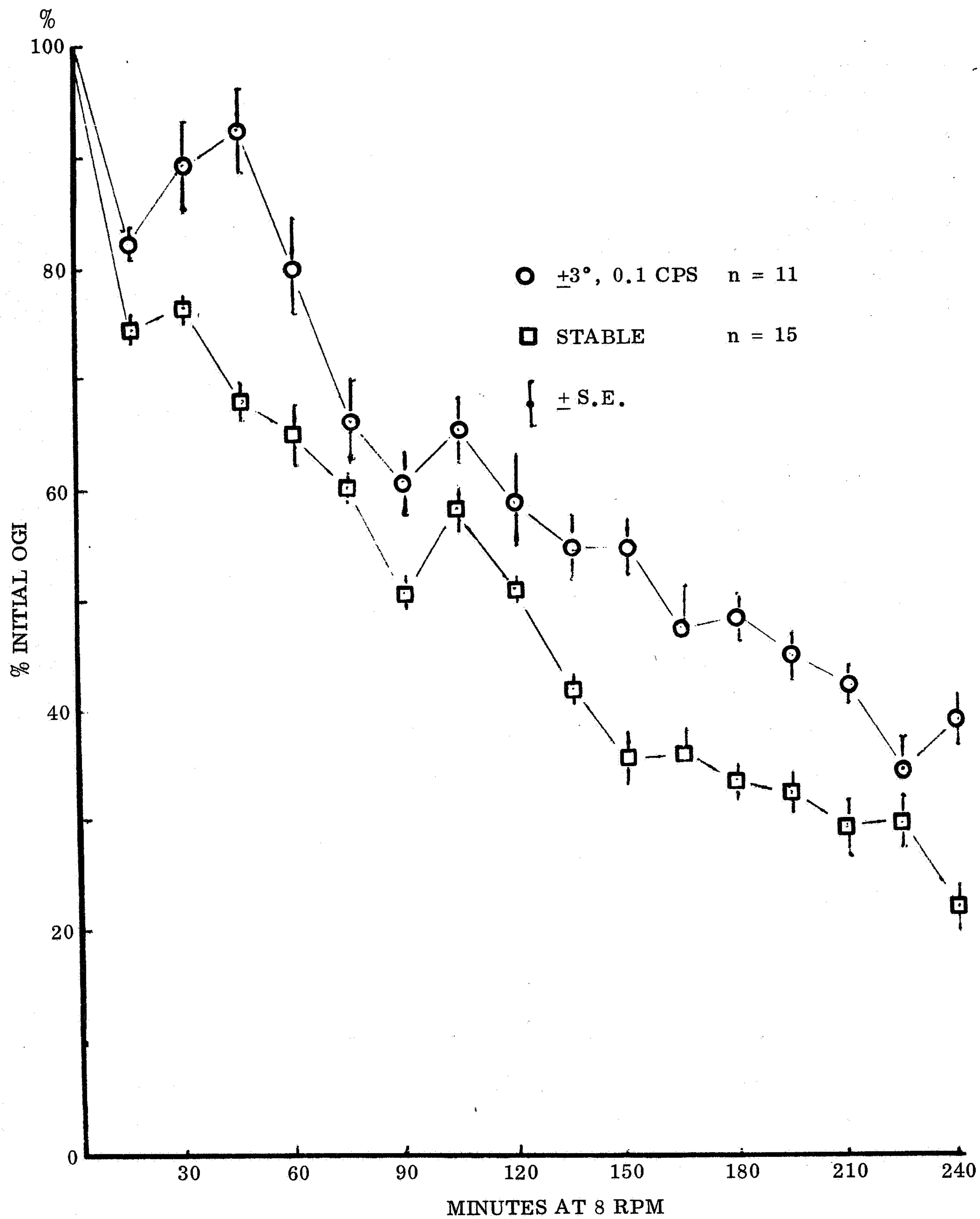


Figure 4-18. Oculogyral Illusion Extinction (All Subjects)

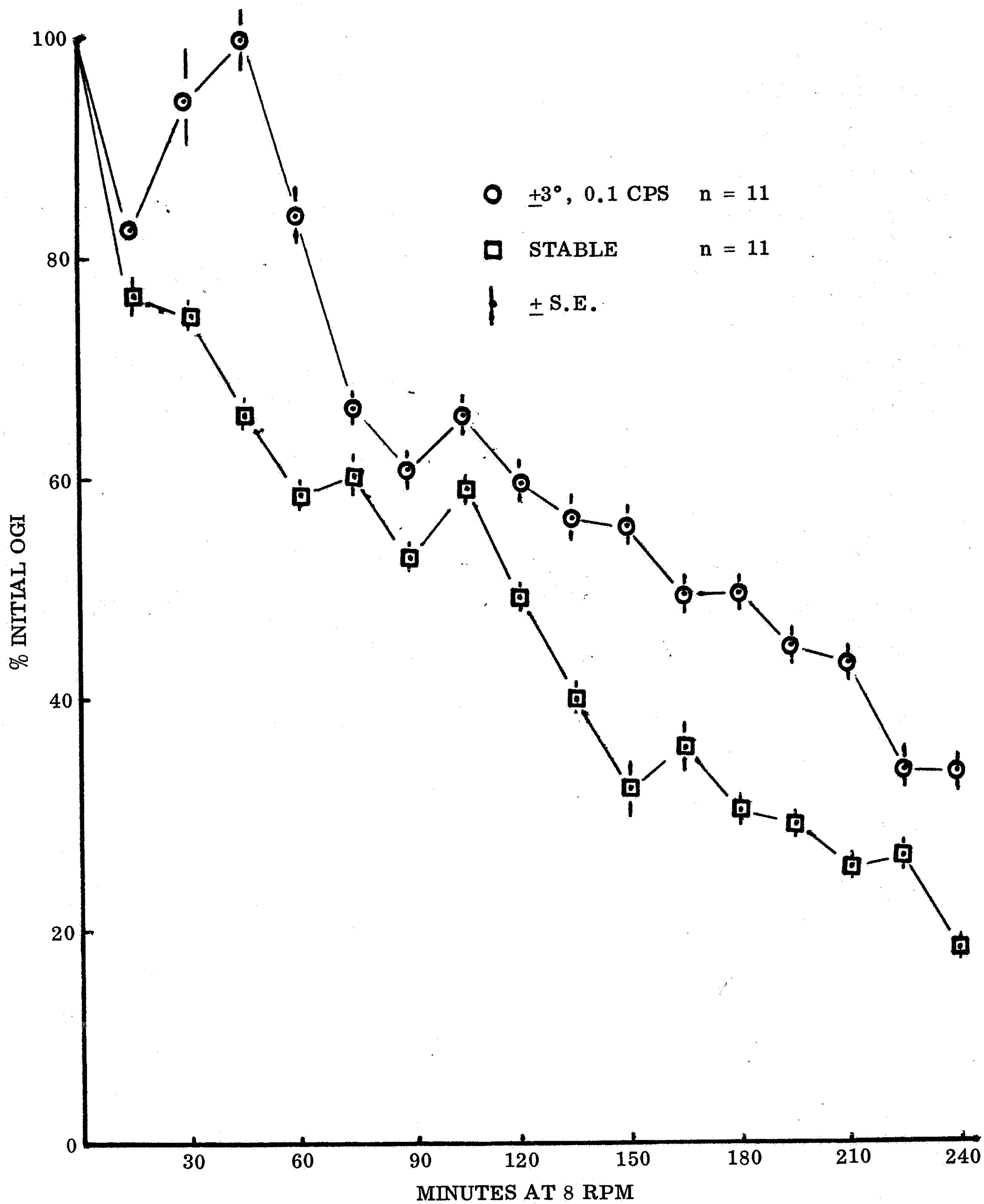


Figure 4-19. Oculogyral Illusion Extinction (Subjects Completing Tests)

A possible explanation lies in the dynamics involved. The subjects were arranged along a radial line in the MRSSS cabin. The X-axis head turns were made in a plane perpendicular to the plane of rotation that passed through the center of rotation. The ±3-degree perturbation of the cabin at 0.1 cps also took place in this same plane, and the stimuli resulting from the subjects' head turn during perturbation was then dependent on the cabin motion at the time of head turn; head turns resulted in a different cross-coupling for each experience and, therefore, could have decreased the rate of habituation. Another important factor is that the perturbation kept a continuous stimulus applied to the semicircular canals; the cupulae were either being stimulated or recovering and, therefore, could be expected to have a decreased sensitivity, being in a partial refractory state.

The raising of the threshold due to a continuous low-level excitation would also explain the feeling expressed by subjects and examiners that rotation seemed to be less disorienting with perturbation than without.

No explanation can be offered for the simultaneous dip in both curves at 90 minutes of testing. This represents six individual test runs and the small distribution of data points would indicate a consistent response but no cause has been found to attribute it to.

Table 4-3 lists the duration of OGI resulting from caloric stimulation before and after four hours of rotation at 8 RPM with and without perturbation. No difference appears to exist between the stable or perturbating conditions, but a very consistent decrease is observed in the time of illusion when pre- and post-rotation values are compared. Six control subjects, tested without rotation but with a four hour interval between irrigations, did not show this decrease in OGI response duration. Subjects who did not have strong illusions resulting from irrigation of both ears prior to testing were not retested after rotation, and caloric data from subjects who did not respond from stimulation in both ears after rotation were also discarded.

Table 4-3. Caloric Illusion Duration in Seconds

Left Ear			Right Ear		
Pre-Rotation	Post-Rotation	Δ	Pre-Rotation	Post-Rotation	Δ
8 RPM - Steady					
115	61	-54	51	59	8
125	41	-84	136	29	-107
106	74	-32	121	58	-63
206	84	-122	115	83	-32
144	109	-33	139	64	-75
142	46	-96	100	52	-48
82	99	17	85	99	14
69	45	-14	94	36	-58
8 RPM with ±3°, 1 CPS Perturbation					
114	97	-17	114	65	-49
140	103	-37	156	88	-68
110	147	37	106	110	4
200	42	-138	62	35	-27
109	60	-49	181	108	-73
176	44	-32	141	122	-19
49	36	-13	52	34	-18
61	21	140	94	43	-51
Control 0 RPM - Steady (4 hr. repeat)					
182	191	9	170	173	3
59	50	-9	83	112	29
189	198	9	124	116	-8
41	54	13	58	60	2
174	195	21	156	165	9
166	186	20	119	114	25

The consistent decrease in response of the remaining subjects could reflect a lack of recovery from the first caloric stimulation. There was a period of five hours or more between irrigations which should have allowed resensitization. An attractive interpretation of the data would be that it indicates a decrease in receptor sensitivity as a result of transference. Such an interpretation would give function to the efferent nerves of the labyrinth, but other workers have not been able to demonstrate such transference.[16, 18, 19]

Table 4-4 presents the "Oculogyral Illusion Durations", i.e., what lack of extinction occurred when repeated X-axis head turns were made, 45 degrees to the right shoulder, every 15 minutes. The OGI time was recorded for right and left motions at the beginning and again at the end of the test period. This procedure has been used to demonstrate the specificity of vestibular habituation to a given motion and the lack of transfer of habituation to non-stimulated receptors.

Using nystagmus as a criterion in addition to the subjective OGI response to head turns, Guedry, et al[16, 17] have reported on the lack of illusion transfer that was observed when their subjects underwent habituation by repeated right head turns in a stable environment at 7.5 RPM. At the end of their test period a single head turn to the unpracticed left produced an OGI response in 50 of 64 trials, while only 12 of 64 trials (sum of turn and return) had any response at all on a turn to the right. Data from the present study were analyzed in a similar manner; however, because very few subjects had a zero OGI response after four hours of rotation, the duration of the illusion was considered the important criterion of habituation. The results reported here on duration of OGI are not nearly as conclusive as the cited study on nystagmus, although the distribution of responses is quite similar.

The transfer of habituation found in the stable rotation of the present study does not agree with that of the other authors[16, 18, 19] and can only be explained by assuming that the unpracticed head turn was not totally isolated from the environment and that some stimulation was somehow being perceived by the supposedly dormant receptors. These stimulations must have been small as the subjects used a bite bar to limit

Table 4-4. Transfer of Habituation
Illusion Duration in Seconds

Repeated Head Turns to the Right - Conditioned

	8 RPM - Stable				8 RPM ±3° @ 1 cps			
	Pre		Post		Pre		Post	
	℄-R	R-℄	℄-R	R-℄	℄-R	R-℄	℄-R	R-℄
$\bar{x}$	12.2	8.0	3.5	3.3	12.4	6.7	4.4	5.5
σ	2.7	2.8	3.1	2.7	5.4	3.9	2.9	3.4
n*	10	13	14	13	13	14	14	14
Total	20.2		6.8		20.9		9.9	
Reduction	66%				52%			

Single Head Turn to the Left - Non-Conditioned

	8 RPM - Stable				8 RPM ±3° @ 1 cps			
	Pre		Post		Pre		Post	
	℄-L	L-℄	℄-L	L-℄	℄-L	L-℄	℄-L	L-℄
$\bar{x}$	6.9	7.4	4.2	4.0	5.2	6.7	5.6	4.7
σ	3.2	3.8	3.1	2.5	5.8	3.5	3.6	2.9
n*	13	13	14	14	14	14	14	14
Total	14.3		8.2		11.9		10.3	
Reduction	41.3%				13.5%			

Number of Responses

Extent of OGI Response Declines**	8 RPM - Stable Conditioned	8 RPM - Stable Non-Conditioned	8 RPM ±3° @ 1 cps Conditioned	8 RPM ±3° @ 1 cps Non-Conditioned
100-80%	12	6	5	1
80-60%	6	3	5	4
60-40%	5	5	6	5
40-20%	1	3	5	2
20- 0%***	2	11	7	16

* Durations exceeding 2 σ from $\bar{x}$ were deleted.
** Total of turn and return.
*** Includes increases.

head motion. There is, however, a decided lack of transfer to the unpracticed side as well as a reduced magnitude achieved by habituation in the perturbated situation. This reduction, in spite of the apparent stimulation, fits the proposed hypothesis that perturbation raises the cross-coupled threshold of the semi-circular canals. The continuous perturbation, which was in the plane of the head turns, could make the system nonresponsive to small stimuli that provided conditioning to the nonpracticed side during stable rotation.

SECTION 5

RELEVANCE TO SPACECRAFT DESIGN

The study reported here is the first attempt, to the knowledge of the authors, to empirically assess the problem of instability for a spacecraft employing artificial gravity by centrifugation. The conclusions are limited by the sinusoidal nature of the perturbations which may not fully represent the space situation. Sinusoidal disturbances are sure to exist, but imposed upon these will be random motions. The sinusoidal pattern is easily anticipated by the subject - consciously or unconsciously. As such, habituation to that motion is probably facilitated.

The sinusoidal perturbations used in these studies with a range of vehicle angular velocity were as severe as have been predicted by the vehicle dynamicists.

The three types of tests used represent a divergent approach that compared the pure passive motion of the subject to that of active head motions. In all cases the anticipated decrease in performance did not materialize.

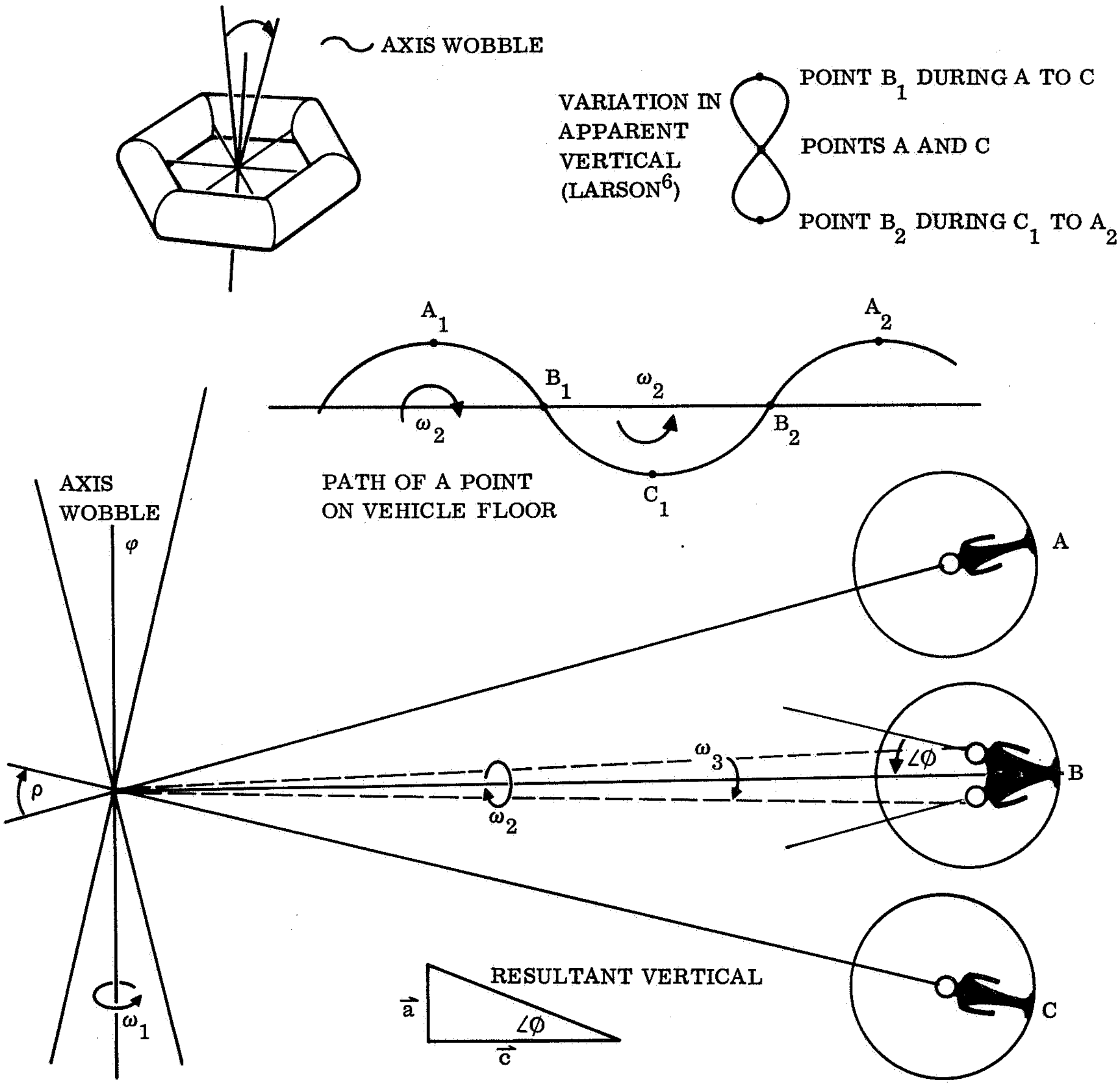
On hindsight, it can be rationalized that this should have been thought of as a possible result of the constant semicircular canal stimulation due to cross-coupled acceleration produced by the product of vehicle rotation and angular perturbation. The observed insensitivity, however, may be due to more than a simple raising of the threshold of this organ.

Cross-coupled acceleration thresholds for the semicircular canal cannot be defined in the same manner as is done in pure angular acceleration. The stimulus is continually varying in vector direction even though the magnitude of the product of angular velocities is constant. During a head turn, a point in the labyrinth as it crosses the vehicle plane of spin has a stimulus vector reduced to zero because the cosine becomes zero in the formula $\alpha = \omega \times \omega \cos \theta$. As that point leaves the plane of spin, the vector quantity increases so there is a continually changing acceleration imposed on each of the six canals. The time each stimulus is applied may be very short -- below that of the time constant required for stimulation. Clark[20], in 1960, estimated the threshold on himself for cross-coupled illusions on a centrifuge rotating at 10 RPM to be 3.6°/sec^2 due to active head turns. Recently Newsom[21] has made a more extensive study, passively tilting immersed subjects at various centrifuge speeds. For turns of low angular velocities (6-10°/sec) the illusion threshold is very close to 3.6°/sec^2 but it varies with the position of the head-turn angle from the plane of spin. The same threshold is not reached, however, if the centrifuge speed is reduced and the angular velocity of the head increased, for this decreases the time of stimulus for a given angle of turn and cross-coupled accelerations of a much higher magnitude are required to reach threshold. In the same study exposure of subjects to Coriolis accelerations of 6°/sec^2 to 90°/sec^2 did not cause nausea or decreased performance.

Figure 5-1 attempts to illustrate the dynamics involved. The MRSSS perturbation simulates the displacement of the vertical due to vehicle wobble. It does not properly simulate the cross-coupling, $\alpha = \omega_1 \times \omega_2$, where the subject is torqued about his Z axis (ω_2) during rotation about a displaced x or y axis (ω_1). A second cross-coupling, $\alpha = \omega_1 \times \omega_3$, results from vehicle rotation and the movement of the head to align the body with the changing angle θ. In the MRSSS this reproduced but is exaggerated by not having the subject's Z axis close to the plane of spin.

The vehicle perturbation of ±3 degrees used in this study is in excess of the mean effective angle through which the man will be realigned in rotogravic space stations. The man displacement is due to the acceleration-vector addition to the centrifugal vector which will be off the normal to the floor, except when the vehicle is at the peak of excursion. The magnitude of this displacement of the vertical will be determined by the cycle duration and radius of the vehicle, but it will never be that of total vehicle wobble.

This is germane because the simulator used in the reported studies used the maximum angle predicted for vehicle excursion ($\angle\varphi$ in the diagram) of ±3 degrees for angle ϕ. In addition, the cross-coupling is a function of the angle from the spin plane. In space, as mentioned before, it will vary a few degrees around zero and, therefore, the cosine



$\vec{c}$ = CENTRIPETAL VECTOR

$\vec{a}$ = ACCELERATION VECTOR DUE TO MOVEMENT OF POINT A TO B, MAGNITUDE DEPENDENT ON FREQUENCY AND AMPLITUDE

ω_1 = ROTATION RATE OF VEHICLE

ω_2 = Z AXIS TORQUE TO SUBJECT

ω_3 = ANGULAR DISPLACEMENT DUE TO VERTICAL ALIGNMENT

ρ = AMPLITUDE OF VEHICLE WOBBLE

$\angle\phi$ = DISPLACEMENT OF VERTICAL (MRSSS SIMULATION)

Figure 5-1. Elements of Vestibular Disturbance due to Vehicle Wobble.

factor will be very small. The simulator perturbation was ±3 degrees; when the resultant is used to establish the normal to the floor, that normal is 87.5° at 6 RPM, 68.2° at 8 RPM and 45° at 12.2 RPM to the spin plane. This means the value by which the cross-product of angular accelerations is being multiplied varies from close to 1 to 0.7 instead of being close to zero as in the space situation. In essence, this means the cross-coupling effect of perburbation used in this study far exceeded that to which the space crews would be exposed.

Observations in the study were limited to a maximum of four hours and the subjects did not move around the simulator. The results, therefore, indicate nothing about how perturbation affects habitability in the rotating environment,which should be the next factor to be investigated.

5.1 CONCLUSIONS

From the results of these few tests it appears that the sinusoidal perturbation anticipated in a rotogravity space vehicle will not unduly complicate specific task performance in a restrained subject.

It is important to extend these observations to a test lasting at least four days to determine if the perturbation is equally innocuous for longer periods, for then considerable instability could be allowed in the rotogravity vehicle.

SECTION 6

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APPENDIX A

CENTRIFUGE FACILITIES (MRSSS)

The MRSSS (Manned Revolving Space Station Simulator) is an 8- by 7- by 14-foot room mounted on a centrifuge arm to provide a 20-foot radius. This trunnioned room can be tilted at any desired angle, and the tilt can be controlled by mechanical actuation to simulate the perturbations of a rotating space station. The MRSSS is inclined on the trunnions so the force field resultant is normal to the floor of the revolving room. This arrangement, shown in Figure A-1, provides a reasonable simulation of a rotating space station.

The simulator is equipped with continuous running water and sewage removal by means of axial rotating couplings. A transfer system for samples and food allows the room to be operated with a crew of four people for a period of weeks without stopping. The interior of the cabin is shown in Figure A-2.

The MRSSS positioning and perturbation system is designed to adjust the test chamber to any angle up to 45 degrees and to perturbate the chamber up to ±3 degrees at any given chamber position. The system consists of two individually controlled hydraulic actuators installed back-to-back on the chamber. Control of these actuators is accomplished by feeding signals from two servocontrollers to servovalves governing hydraulic flow to the actuators.

The 25-inch-displacement positioning cylinder (Figure A-3) controls the angle of the chamber from 0 to 45 degrees and uses an angular displacement potentiometer to obtain the feedback signal for the displacement servocontroller; the resulting chamber angle is displayed on a control console meter calibrated in degrees. Extreme displacement limits (-10 degrees to +55 degrees of angle) are attainable using the perturbation actuator in conjunction with the position actuator. Angular displacement is accomplished at a rate of 1 degree per second. In addition, this system has the capability of being programmed to follow the changing angular velocity of the chamber being accelerated on the centrifuge.

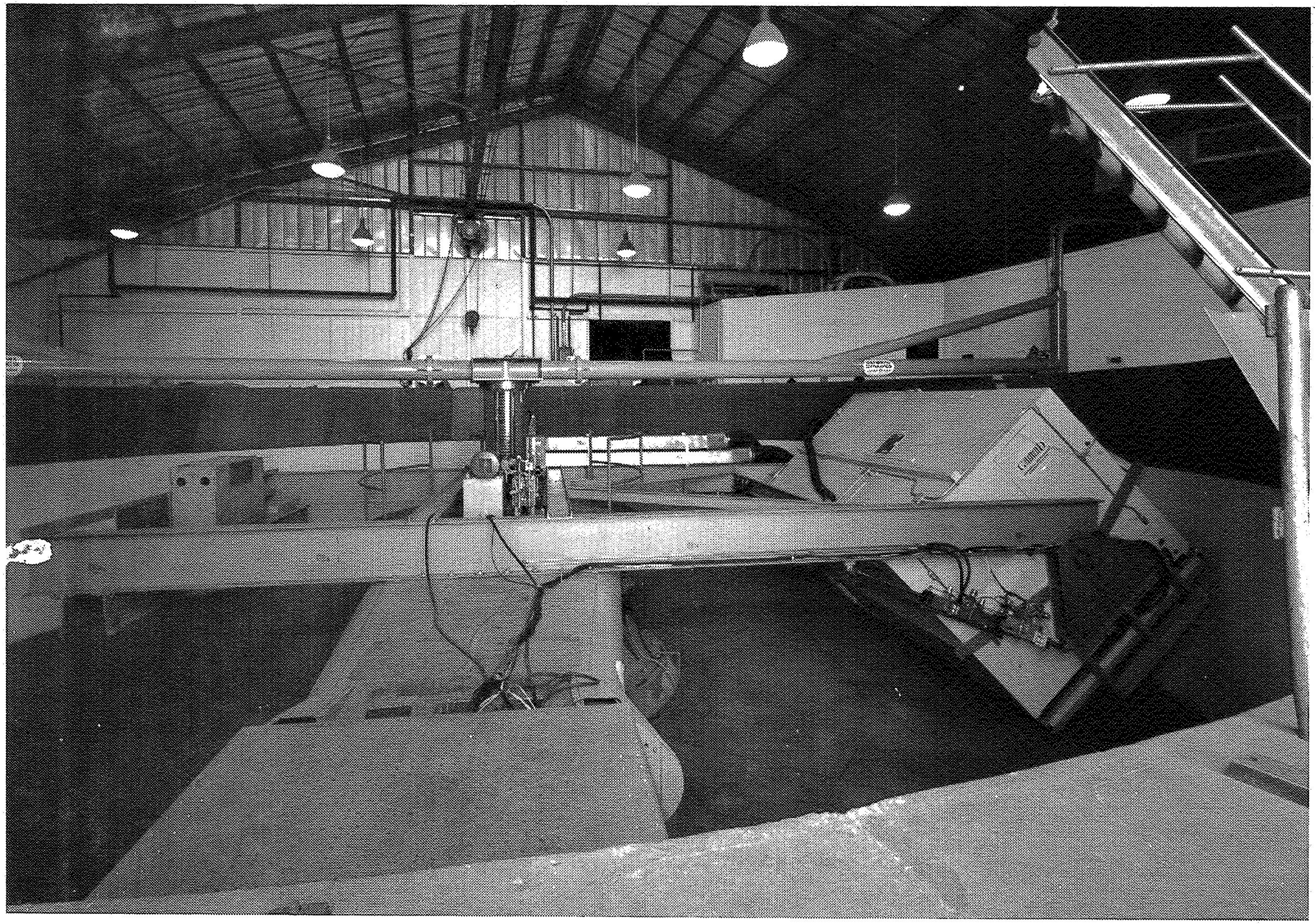

Figure A-1. Manned Revolving Space Station Simulator Inclined at 45 degrees

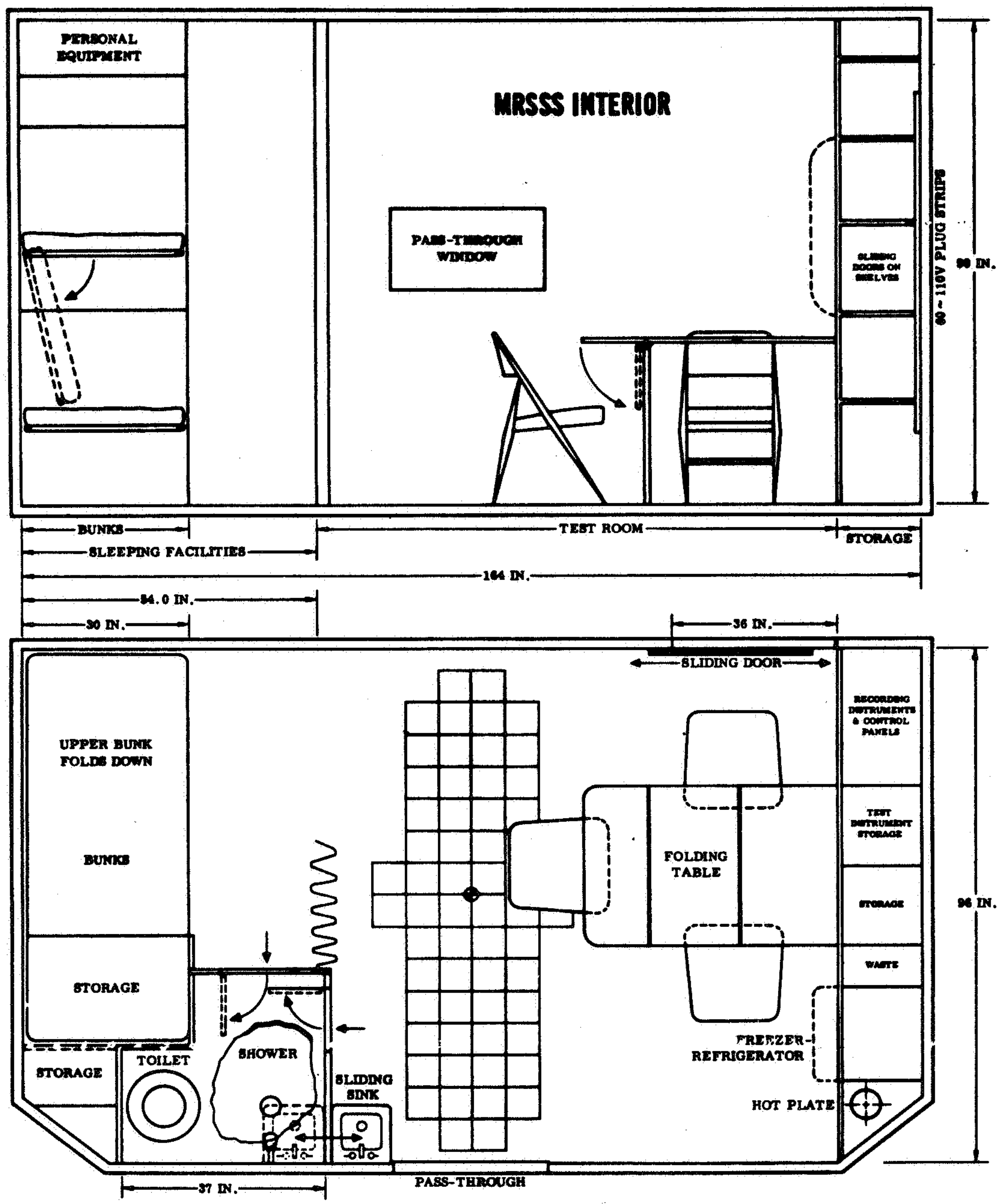

Figure A-2. Cabin Interior of Manned Revolving Space Station Simulator

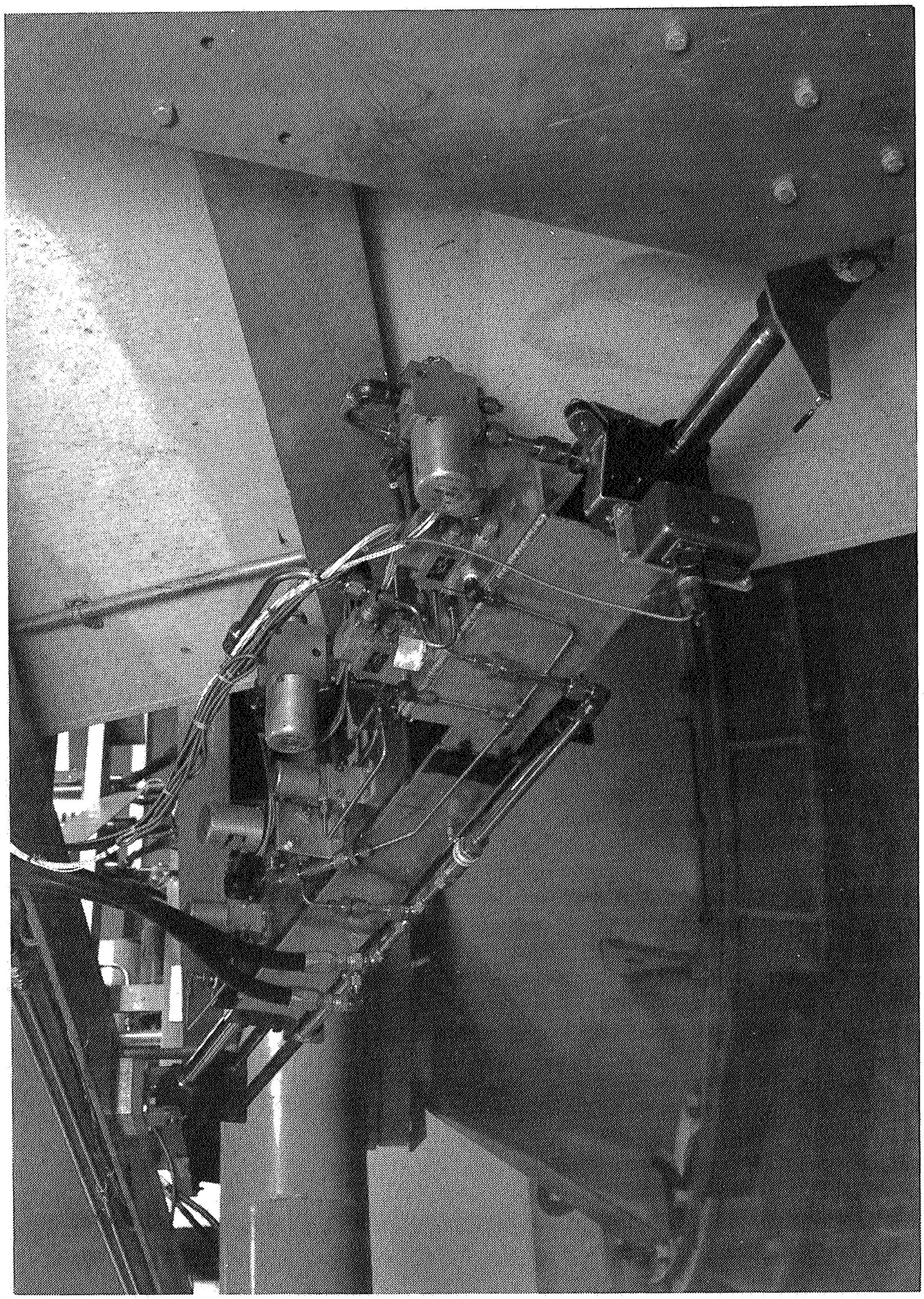

Figure A-3. Back-to-Back Piston used for MRSSS Inclination and Perturbation

Perturbation is accomplished by feeding a signal of given frequency to the perturbation controller, which activates the servovalve controlling the (12-inch stroke) perturbation actuator. Feedback for the perturbation controller is supplied by a linear motion transducer. Displacement of the perturbation cylinder is reflected in inches of travel on a meter located at the control console. The perturbation system, shown schematically in Figure A-4, is capable of oscillations of ±3 degrees about any fixed position of the chamber from 0 to 45 degrees. The nominal sine wave frequency is 0.1 cps. Any wave form may be programmed into the perturbation system (subject to the angular velocity limitation of 1 degree per second).

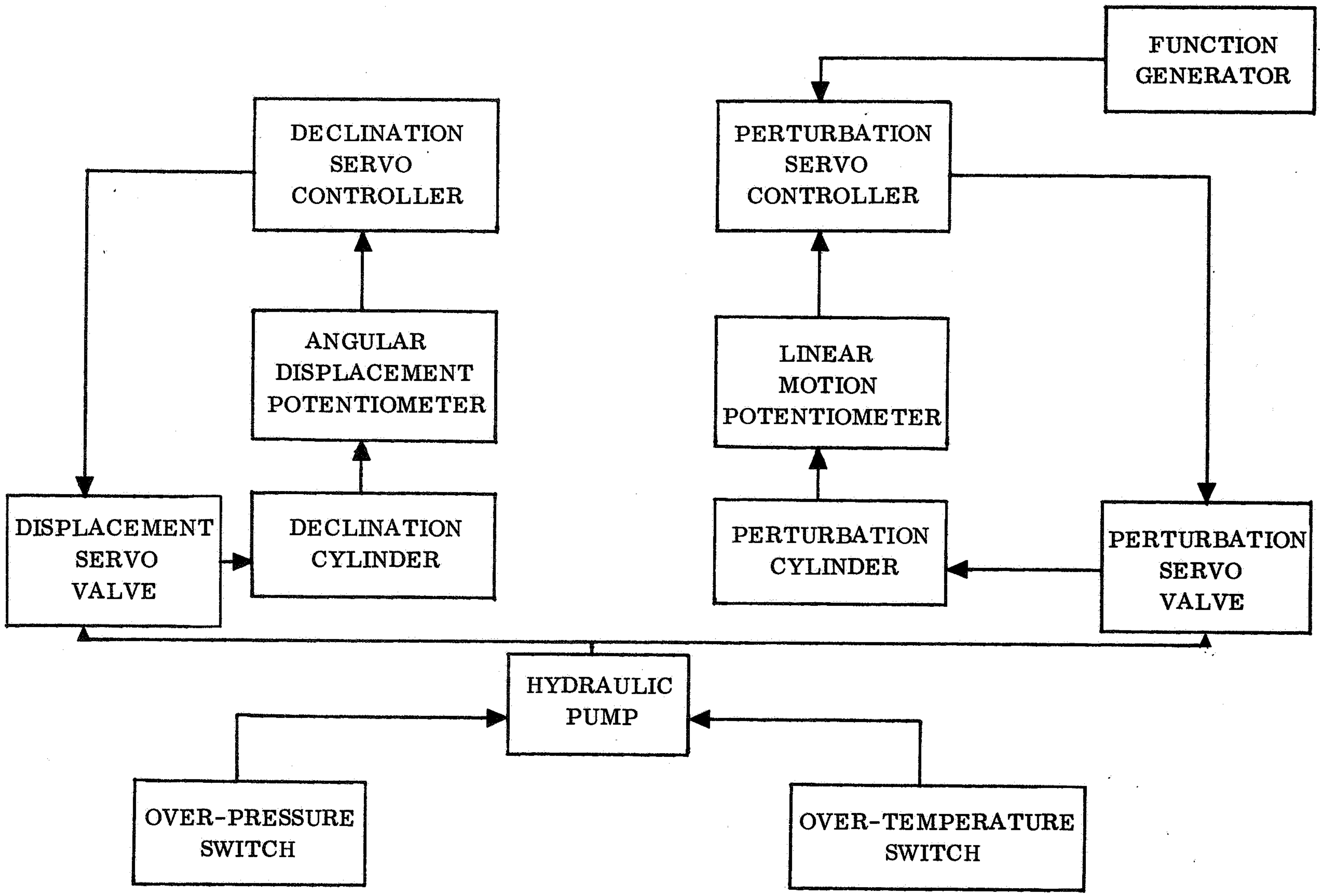

Figure A-4. MRSSS Positioning and Perturbation System

APPENDIX B

MODEL 766 P-M PERFORMANCE CONSOLE

The Perceptual-Motor Performance Console, Model 766, is an improved version of a testing device developed by BioTechnology, Inc., for NASA under contract. Under that contract, a prototype console containing 18 tests of primary perceptual-motor abilities was constructed. The tests were derived from an extensive review and analysis of the technical literature, with particular attention to factor-analytic studies of perceptual-motor performance. In selecting specific items for inclusion in the test battery, consideration was given to the kinds of activities performed by astronauts as derived from a task analysis of the Gemini Mission. The assumptions and procedures used in the development of the task and a detailed description of the console are reported elsewhere.[1]

All 18 tests were retained in the console used for this study. These tests are summarized in Table B-1. In the prototype console, all functions were contained within a single unit. The current version is comprised of two separate consoles: 1) an experimenter console that contains all test setup, programming, and scoring components, and 2) a subject console that contains only test display and response elements.

One of the principal criteria used in selecting factors for test selection was that the factors should conform with the development of equipment with which to study the effects of the space environment on human performance. Within this framework, however, tests are limited to those performances that would be required in the operation and control of space vehicles, and are not concerned with problems of entering and leaving the vehicle or other extravehicular activities.

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[1]J. F. Parker, Jr., R. E. Reilly, R. F. Dillon, T. G. Andrews, and E. A. Fleishman, Development of Tests for Measurement of Primary Perceptual-Motor Performance, NASA Contractor Report CR-335, December 1965.

Table B-1. Summary of Selected Ability Factors

Ability Factor	Description of Behavior	Adequacy of Identification	Associated Space Activity
Fine Manipulative Abilities			
Arm - Hand Steadiness	Hold arm and hand steady while fully extended.	High loadings in several studies	Use utility pole to reach switches.
Wrist - Finger Speed	Make rapid, repetitive tapping movements	High loadings in several studies	Perform general keyboard operations.
Finger Dexterity	Manipulate small objects with fingers	High loadings in several studies	Manipulate switches
Manual Dexterity	Manipulate large objects with hand	Varied loadings in several studies	Use larger control handles
Gross Positioning and Movement Abilities			
Position Estimation	Reach for specific locations without use of vision	Low loadings on single study	Grasp peripheral control switches
Response Orientation	Make appropriate directional response to non-spatial stimulus	Varied loadings in several studies	Use digital displays in vehicular control
Control Precision	Make fine, controlled positioning movements	Varied loadings in several studies	Use attitude and maneuver controls
Speed of Arm Movement	Make discrete, rapid arm movements	Varied loadings in several studies	Perform rapid sequence of control settings
Multilimb Coordination	Use hands and/or feet simultaneously	Varied loadings in several studies	Use attitude and maneuver controls
Position Reproduction	Repeat discrete arm-hand movement without aid of vision	Low loadings on single study	Intermittent use of peripheral controls
System Equalization Abilities			
Movement Analysis	Differentiate target velocity and acceleration	High loadings in single study	Perform rendezvous maneuvers in visual mode
Movement Prediction	Integrate target motion components to estimat e future target position	Low loadings in single study	Perform rendezvous maneuvers in visual mode

Table B-1. Summary of Selected Ability Factors, Contd

Ability Factor	Description of Behavior	Adequacy of Identification	Associated Space Activity
Rate Control	Control vehicle having first order system dynamics	Varied loadings in several studies	Operate attitude and maneuver subsystems
Acceleration Control	Control vehicle having second order dynamics	Varied loadings in several studies	Operate attitude and maneuver subsystems
Perceptual-Cognitive Abilities			
Perceptual Speed	Make rapid visual comparisons of display elements	Low loadings in several studies	Scan complex system displays
Time Sharing	Divide attention among several displays	High loadings in single study	Monitor control panel
Reaction Time Ability			
Reaction Time	Respond as rapidly as possible to discrete signal	High loadings in several studies	Make control responses where time is critical
Mirror Tracing Ability			
Mirror Tracing	Use mirror-image display to perform directional hand-arm movements	Not identified in factor analytic studies	Use panel mirrors to locate and operate peripheral controls

To obtain information concerning activities that will be performed by space personnel, a number of individuals within NASA were interviewed. The consensus was that the activities required during a Gemini mission, including rendezvous and docking, are representative of the type of activities that will be involved in the operation and control of any space vehicle. In addition, more is known at this time concerning the Gemini mission than any other programmed space voyage. Accordingly, a complete task analysis was prepared for a Gemini mission using information supplied by NASA.

The 18 factors finally selected for inclusion in the test battery and their associated tests are described in detail in the following paragraphs. The numbers and letters in parentheses designate items required in test performance; these items are identified in Figures B-1, -2 and -3.

<u>Arm-Hand Steadiness (AHS):</u> The subject attempts to hold stylus (B_1) within aperture (1) without touching rim for three equally spaced 10-second trials within a one-minute period. Score is total number of contacts during the 30 seconds of testing.

<u>Wrist-Finger Speed (WFS):</u> Using the first two fingers of his preferred hand, subject attempts maximal number of taps back and forth between the two centrally located microswitches (2) during three equally spaced 10-second trials within a one-minute period. Score is number of presses during the 30 seconds of testing.

<u>Finger Dexterity (FD):</u> With template (D_1) fastened centrally on his console, subject attempts maximal speed in working from the bottom to the top of the template, alternately screwing the joined hex and square (D_2) to the template, then separating the hex and the square and screwing each to the template, then joining the hex and square, etc. Score is time in seconds from beginning to completion.

<u>Manual Dexterity (MD):</u> With color-coded board (A_1) fastened centrally on his console, subject attempts maximal speed in twice working clockwise around the board, inserting in it and retrieving from it a comparably coded block (A_2) using his preferred hand.

The following restrictions are imposed: he is required to pick up the block by grasping the projection corresponding to the receptacle next in sequence, rotate the block in his

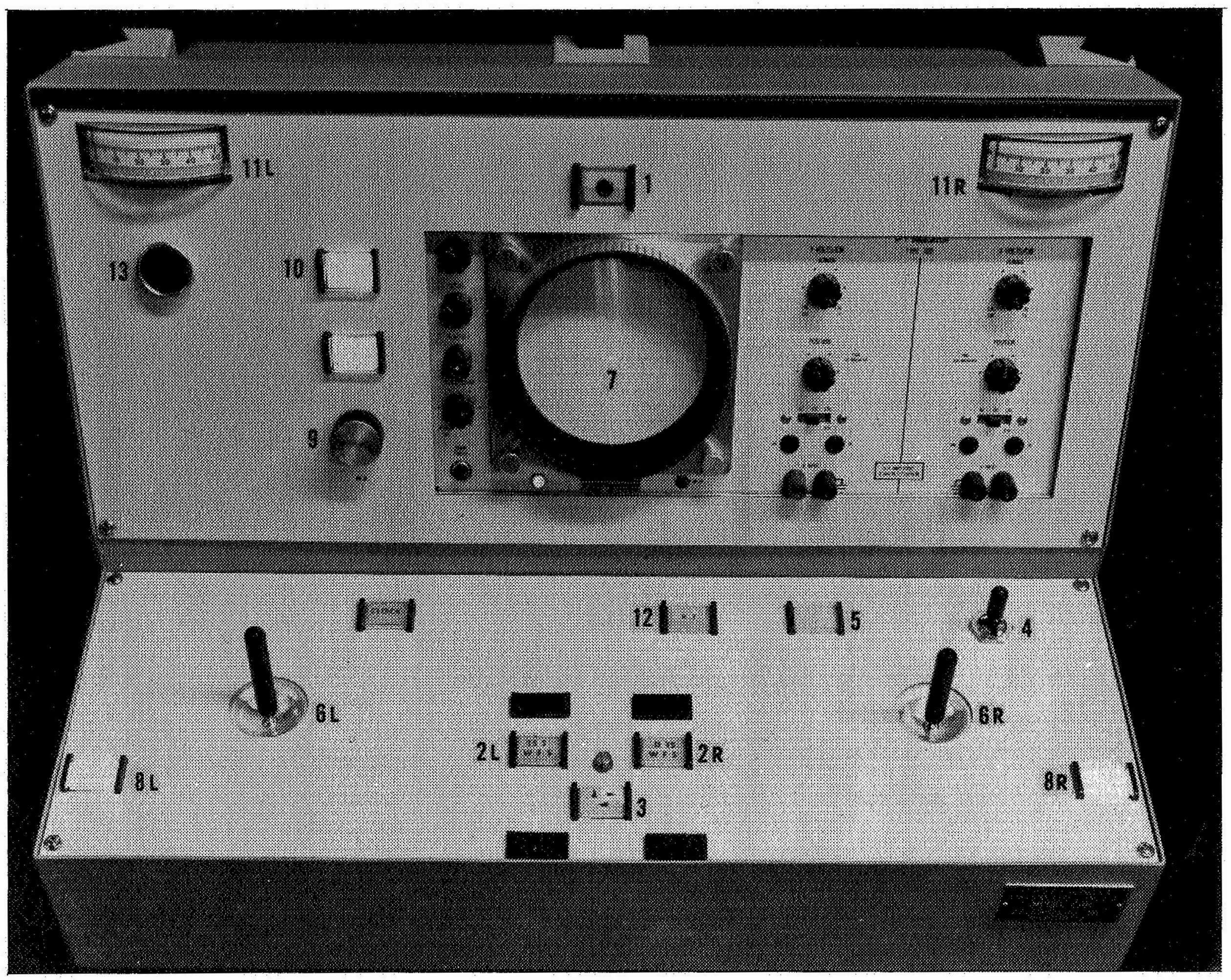

Figure B-1. Perceptual-Motor Tester, Subject's Console

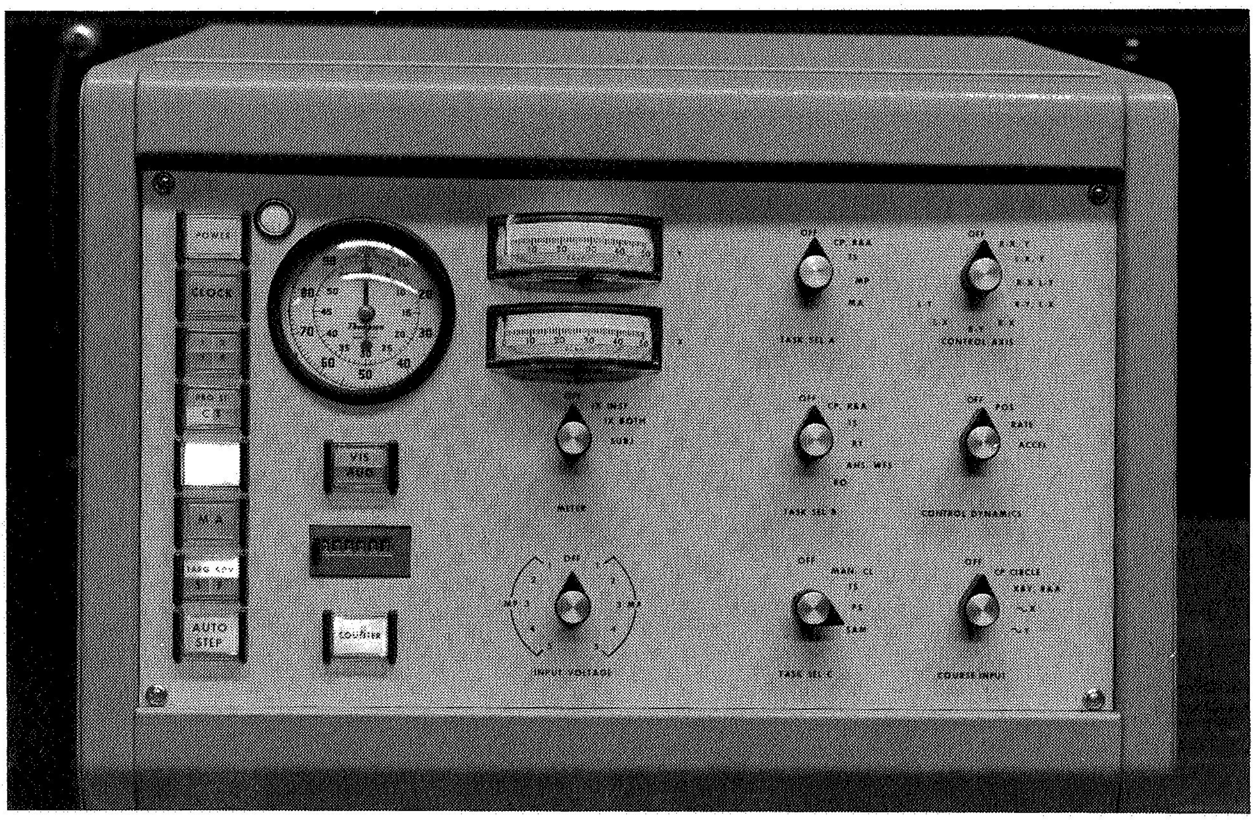

Figure B-2. Perceptual-Motor Tester, Examiner's Console

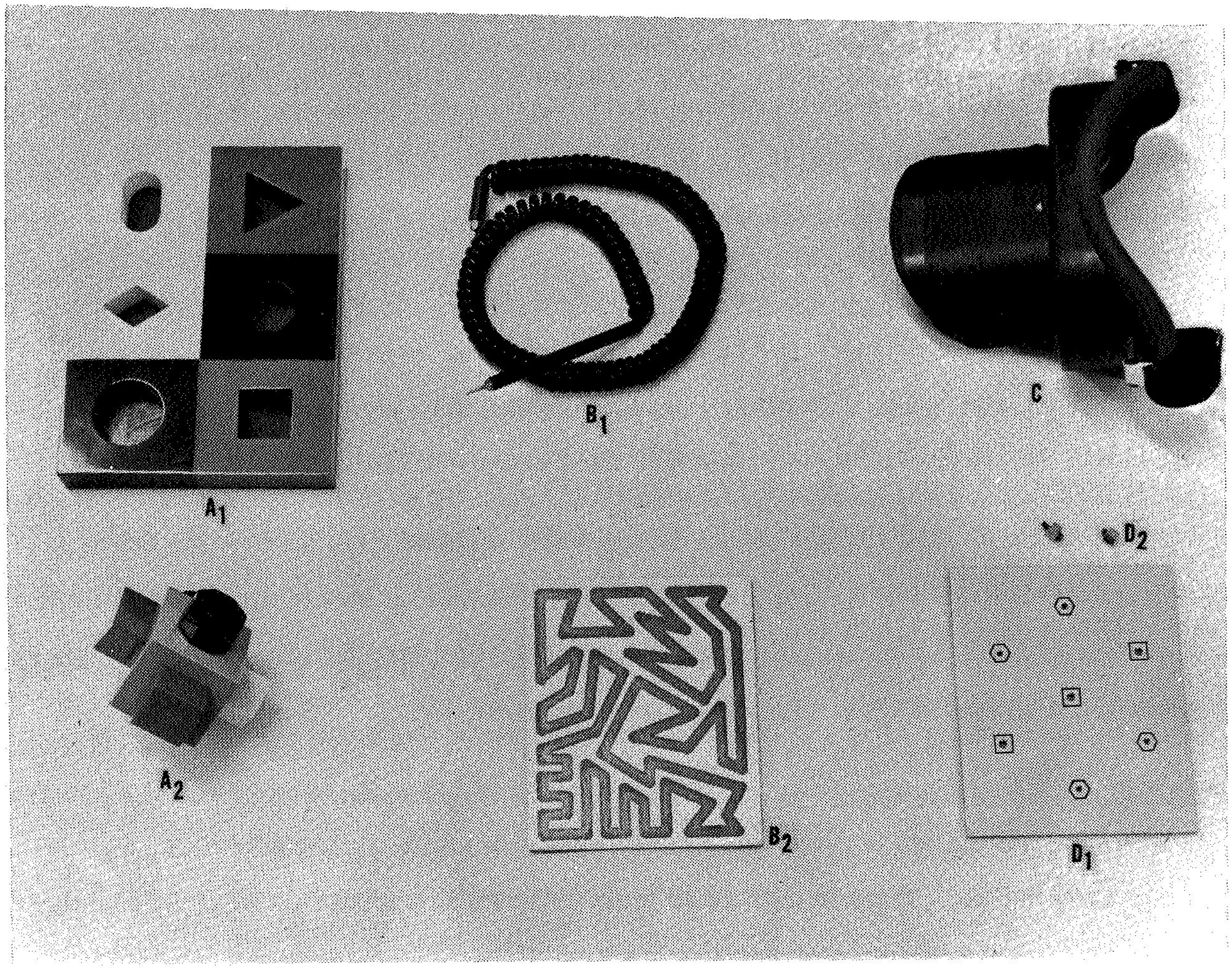

Figure B-3. Perceptual-Motor Tester Accessory Items hand and insert it, then retrieve it, etc.; he is not allowed to touch the central (gray) portion of the block during insertion and retrieval. Score is total time in seconds for two complete circuits of the board. Figure B-4 shows this test in progress.

Position Estimation (PE): Subject responds to lighted arrow (3) by looking up at one of three designated targets above the console (not shown), then looking down and attempting to touch the bullseye in the appropriate target blindly. Concentric rings on each target allow 0 (missed entire target), 1, 2, and 3 (bullseye) scoring for each trial. Score is maximum points for 10 separate trials. Figure B-5 shows the test in progress.

Response Orientation (RO): Subject responds as quickly as possible with correct position (left, forward, right, or back) of four-position switch (4) to each of four colors (green, red, white, or blue, respectively) as they are displayed on the micro-switch (5). Score is total time in seconds for 24 correct responses.

Control Precision (CP): With his preferred hand, subject manipulates the corres-ponding control lever (6L or 6R) in a clockwise direction to superimpose his pursuit dot on a target dot that moves clockwise on the CRT display (7). Score is total track-ing error integrated over a one-minute tracking trial.

Speed of Arm Movement (SAM): Using the fingers of his right hand, subject attempts to strike his left and right lateral microswitches (8L and 8R), in that order, as quickly as possible. Time is measured from left switch percussion to right switch percussion. Score is sum of times for five trials.

Multilimb Coordination (MLC): In this two-handed tracking test, the subject attempts to keep the dot in the CRT (7) centered against programmed velocity changes. The right-hand lever (6R) controls horizontal correction rate; the left-hand lever (6L) controls vertical correction rate. Score is total integrated error over a one-minute trial. Figure B-6 shows the test in progress.

Position Reproduction (PR): Identical to (PE), except that instead of the blind reach being preceded by a visual fix only, the blind reach is preceded by a visual reach.

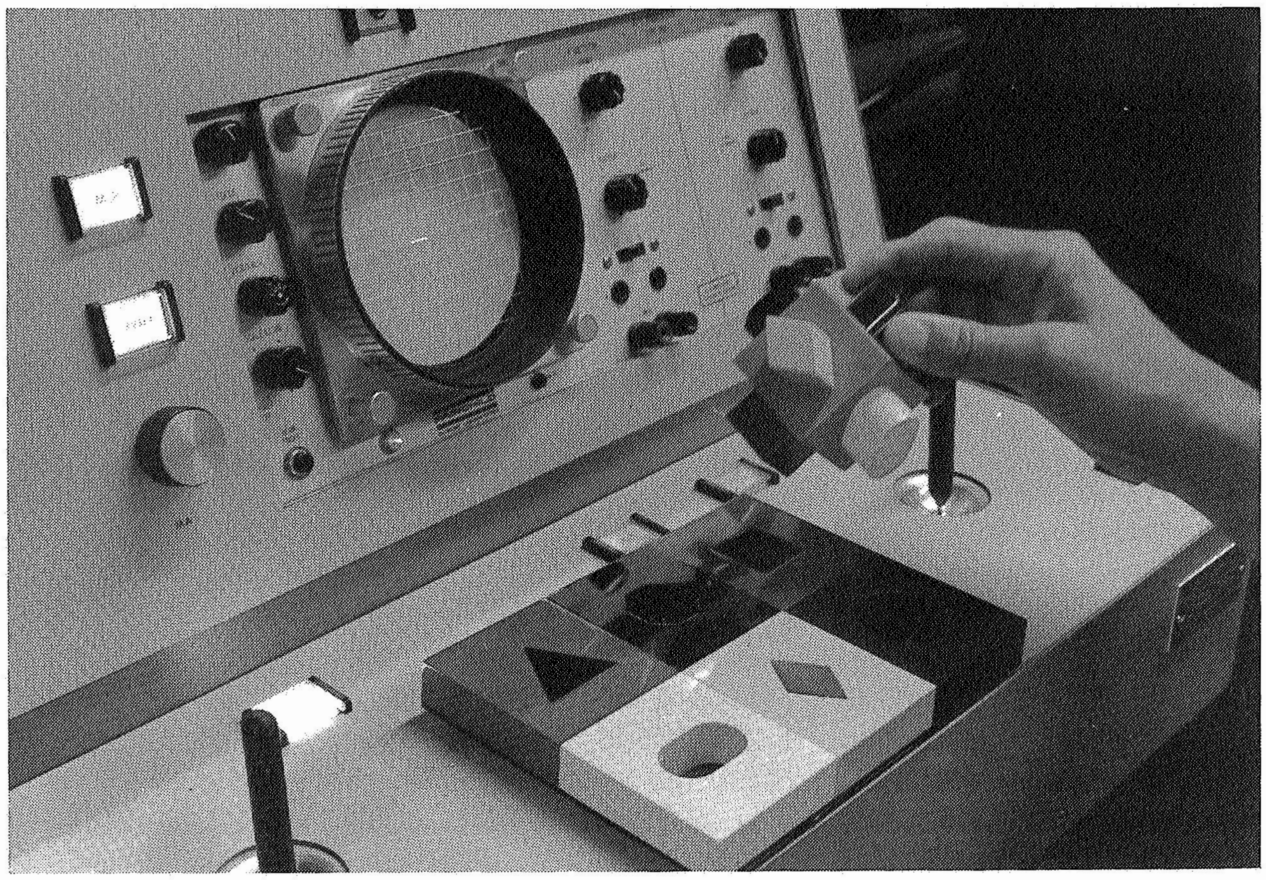

Figure B-4. Subject Performing Manual Dexterity Test

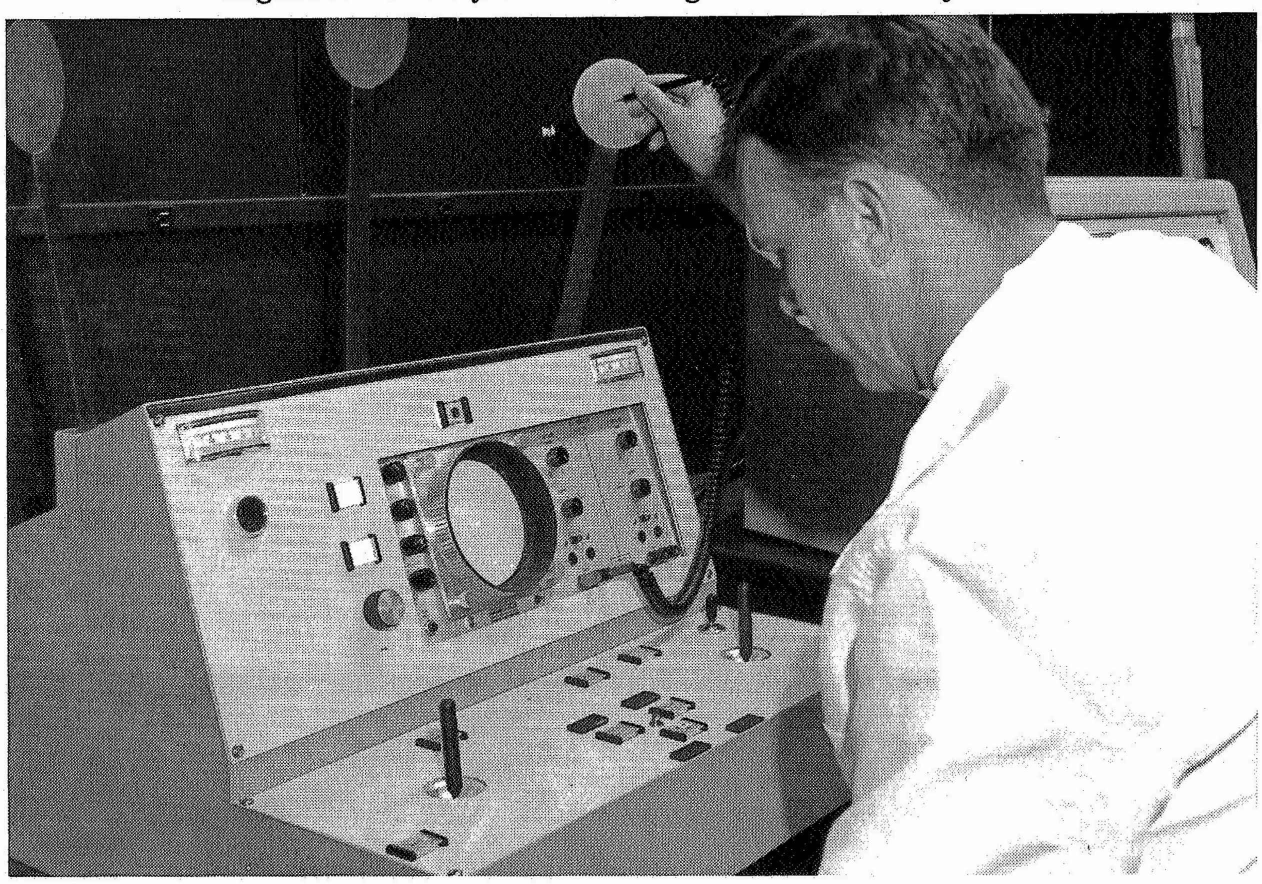

Figure B-5. Subject Performing Position Estimation Test

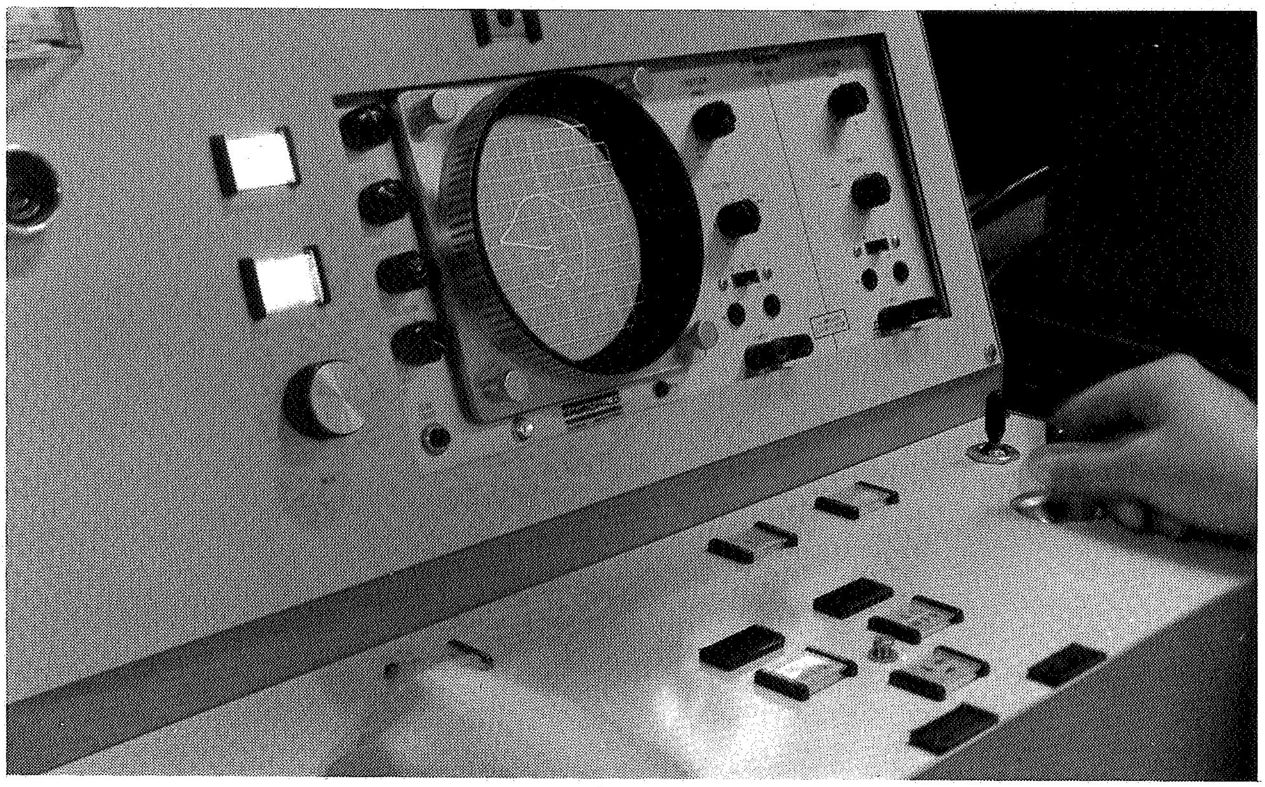

Figure B-6. Subject Performing Multi-limb Coordination Test

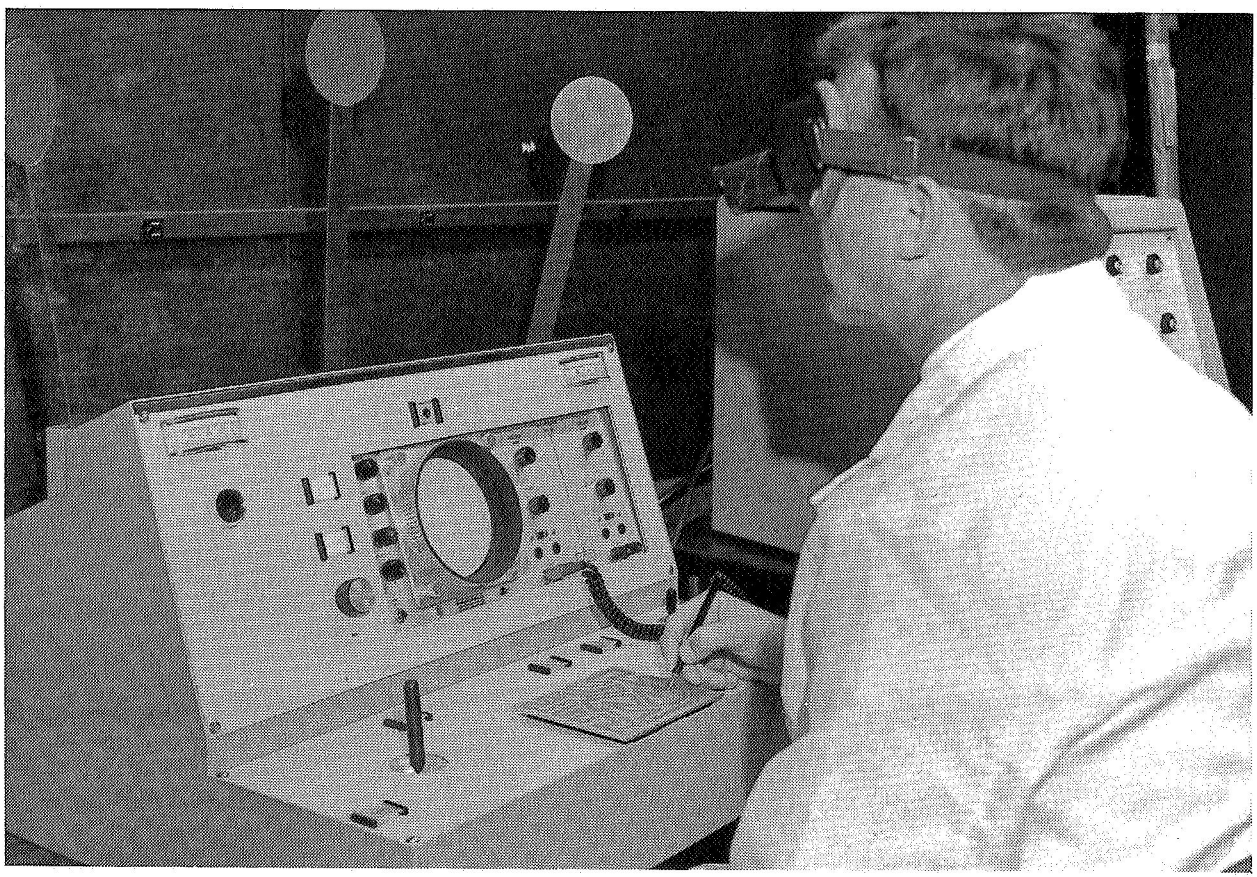

Figure B-7. Subject Performing Mirror Tracing Test

Movement Analysis (MA): Using as many experimental adjustments as he wishes, subject attempts to decelerate dot in the CRT (7) as it moves horizontally across the scope from left to right until he perceives it as a constant velocity. He decelerates the dot by adjusting potentiometer (9). Subject is tested for a set of five separate and different acceleration/velocity trials. Score is total error for the five trials.

Movement Prediction (MP): When subject holds MP switch (10) down, target dot on CRT (7) moves in same direction as in MA, but at a constant velocity. It disappears when it reaches the center of the scope, and subject's task is to release MP switch when he estimates the CRT dot would have arrived at the right-hand margin of the scope. Score is the total error for five trials of different velocities.

Rate Control (RC): This is a one-hand, two-axis compensatory tracking task using first-order system dynamics. The subject's task is to keep the target dot on the CRT (7) centered against programmed velocity error by manipulating a control stick (6L or 6R) with his preferred hand. Score is total tracking error integrated over a one-minute trial.

Acceleration Control (AC): Identical to (RC) except that the dynamics are second-order, requiring acceleration corrections by subject.

Perceptual Speed Time (PST): The subject monitors meters as a series of readings are simultaneously presented on each. If the readings are the same, he presses the left-hand microswitch (2L), labeled "S"; if different, he presses the right-hand microswitch (2R) labeled "D". If his choice is correct, the next readings are presented; if he is not correct, an error is recorded and he must make the correct response. Score is total time required to process 24 sets of readings.

Perceptual Speed Accuracy (PSA): Score is total number of errors incurred in processing the (PST) readings.

Time Sharing (TS): Subject monitors both meters (11L and 11R) to detect the onset of pointer movement. When movement occurs, the subject presses the corresponding microswitch (2L or 2R) – both of which are labeled "TS". A timer begins when either pointer begins to move and stops when the correct switch is pressed. Score is accumulated response time required to process 24 events.

Visual Reaction Time (VRT): With finger tips resting lightly on microswitch "RT" (12), subject presses it as quickly as possible when it suddenly illuminates. Score is total reaction time for four trials.

Audio Reaction Time (ART): With finger tips resting lightly on microswitch "RT" (12), subject presses it as quickly as possible when audio signal is emitted by speaker (13). Score is total reaction time for four trials.

Mirror Tracing Speed (MTS): With maze (B_2) attached centrally to his console, subject dons mirrored visor (C) and uses stylus (B_1) to trace the maze in a clockwise direction as quickly as possible while using the mirror image of the maze as the only visual guideline. MTS score is total time to complete one circuit of the maze. Figure B-7 shows this test in progress.

Mirror Tracing Accuracy (MTA): Edges of maze path are conducting, facilitating counting of deviations from path during circuit. Subject is scored on number of deviations while achieving (MTS).

APPENDIX C

USE OF THE EYE MOTION CAMERA FOR DETERMINING VISUAL FIXATION TIMES FOLLOWING CORIOLIS STIMULATION

Loret suggested that the correlation between simulation on earth and the space situation might be assessed if a simulator could be provided with a centrifuge arm sufficiently long that a tolerable spin rate would provide one g radially, with the simulator floor at 45 degrees from the g vector. Then by reclining a subject in a chair at 45 degrees to the simulator floor it would be possible to position his Z axis in the plane of spin (with his head toward the spin axis), or at right angles to the plane of spin (with his feet toward the center of rotation), as seen in Figure C-1. In any position, his Z axis would always be displaced from the gravito-centrifugal resultant by 45 degrees, providing a constant otolith stimulus in all head-turn planes.

The Convair MRSSS (Manned Revolving Space Station Simulator), which is an 8- by 14- by 7-foot room mounted on a large centrifuge (Figure A-1), is capable of providing such an environment. The study was completed under a previous contract.[1] During that study, a techinque was developed to determine the direction of gaze made by subjects attempting to fixate on a point of light. Following head turns in the various orientations under study, it was found that the performance decrement was correlated with the time it took for the gaze to fixate on target.

Task II of the present contract uses the same eye motion camera technique and subject orientations to investigate the possible effects of superimposed perturbation.

As in the preceding studies, the spin rate of 12.2 rpm at the 20-foot radius provided one g radially. The floor of the simulator was inclined 45 degrees from its static horizontal, which aligned the gravito-centrifugal resultant at right angles to the simulator floor. A chair was constructed to incline the subject 45 degrees on his side. This position maintained his Z axis at a constant angle of 45 degrees from the inertial

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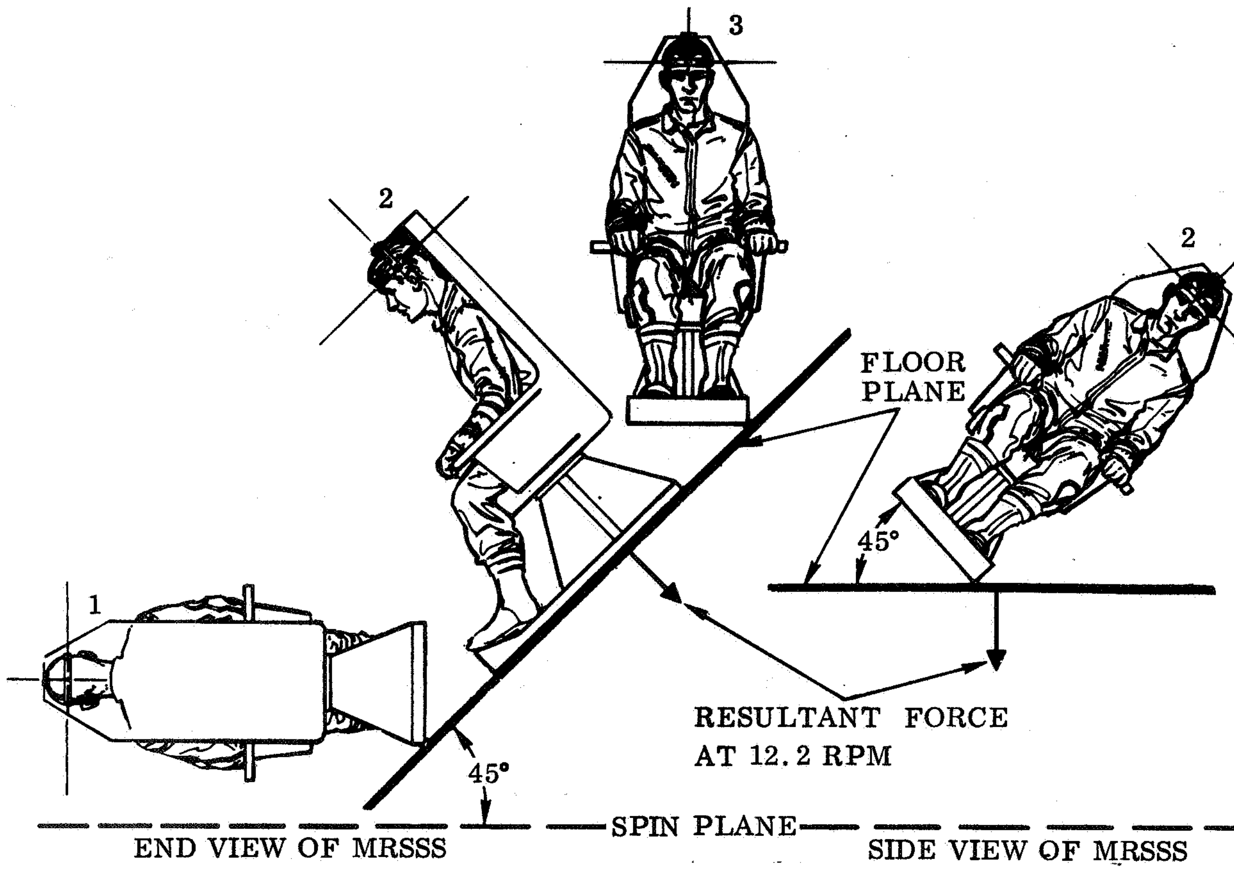
1. Final Report Study of Performance in a Revolving Space Station Simulator as a Function of Head Rotation about Y and Z Cranial Axes. NASA Contract NAS 9-5232, Manned Spacecraft Center, Houston, Texas, Nov. 1966.



SUBJECT ORIENTATION TO MOTION	POSITION	ANGLE BETWEEN SPIN AND RESULTANT (degrees)	ANGLE BETWEEN Y-AXIS HEAD-TURN PLANE AND SPIN PLANE (degrees)
Forward	1	45	0
Backward	3	45	90
Toward Center of Rotation	2	45	45

Figure C-1. Orientation of Subjects in MRSSS

resultant for any chair orientation. With the subject facing the direction of centrifuge spin (position 1 in Figure C-1), head turns (or nods) about the Y axis were in the plane of spin (creating minimal Coriolis effect). When he faced against the direction of spin (position 3 in Figure C-1), Y-axis turns were 90 degrees out of the plane of spin (creating maximal Coriolis effect). Half-way between, when facing the spin axis (position 2 in the figure), Y-axis head turns were 45 degrees from the plane of spin. Orientation angles for the various subject positions are shown in Figure C-1.

The inclined chair and the head restraint system used in this study restricted head motions to the Y-axis by use of an adjustable sleeve-bearing for the Y-axis and stops for other degrees of freedom. A number of adjustments were available — and needed — to provide full ease of head movement in Y-axis movements.

Anthropometric differences greatly affected the point of Y-axis rotation, and there was also considerable difference in the way the head was nodded. Some subjects used most of the cervical area in the motion, others flexed primarily at the atlanto-occipital joint. It was found that the turns had to be completely comfortable for the subject or he fatigued quickly.

The Y-axis turns were recorded on a Sanborn 150 polygraph from potentiometers mounted at the center of axis rotation. Readouts were calibrated prior to testing each subject.

For oculogram recording, a point source display was required. The basic RATER was modified by installing remote buttons and collimating the light to present a one-degree visual angle. The basic test sequence totaling 150 seconds of testing consisted of ten 15-second trials separated by 20-second rest intervals. The beginning of each 15-second trial was signaled by a light above the subject's head. To view the RATER color display, the subject then executed a Y-axis 70 degree head turn. Electro-oculograms were recorded on each head turn for both horizontal and vertical components, and results correlated with RATER scores for each head-turn orientation.

The techniques developed in NAS 9-5232 with the inclined chair were used with the RATER as a performance test. This test provides a point of fixation for the subject. The subject responds to four colored lights by pressing the appropriate button to obtain the next signal.

A Westgate Laboratories EMC-2F eye-motion camera was used to record absolute position of gaze. This instrument reflects the eye spot through a periscope onto the back of the film; the spot's intensity penetrates to the emulsion at the same time the conventional lens system photographs the field of regard. The eye camera is integrated into the head restraint. A 100-foot roll of 16mm film is loaded into the canister on the left side of the subject's head, with the film guide carrying the film through the camera to the take-up reel on the right side of the subject's head. Eastman 4-X Type 7224 film was used to provide high sensitivity to the eye spot. Photographs were made at 8 frames/second, with 4 lens opening f16 and normal ambient illumination.

The Response Analysis Tester (RATER) was used to measure performance. RATER tests correct rote responses to lights of four different colors or test symbols. The subject responds to each color by attempting to press the correct button on a console for that color light. When the correct button is pressed, the next color appears. Total responses and correct button responses are recorded automatically.

Adaptation of the eye camera for use in this study involved meeting two primary test requirements: 1) prevention of significant (more than ±0.5 degree) relative movement between the subject's head and the camera optics, even during the sequences of head turns and 2) support of the camera and head-restraint masses so that the subject could move his head with a freedom approaching that when unencumbered.

To prevent cranial movement relative to the camera optics, the inflexible continuity of the maxillary arch was used with a bite bar having an exact dental impression of each subject. Taking a direct permanent plastic impression would involve a lengthy curing period, the discomfort of the exothermic reaction, and the possibility of dental complications that might require emergency professional aid. Using a combination of Tra-Ten impression trays and Hydro Jel impression material solved this problem.

Only an upper impression tray was required. This was reduced in depth and shortened to preclude any subsequent stimulus to the soft palate during use, and was epoxied to a stainless steel frame bar for securing to the head restraint for testing.

The impression colloid is formed by homogenizing powder and tap water using a spatula and rubber bowl. The homogenate is then smeared on both surfaces of the tray and an impression taken of the subject's bite for two minutes. This procedure produced accurate upper dental impressions (Figure C-2). For all subjects, the impressions withstood almost continuous use for three to four hours without breaking down, yet could be peeled instantly from the tray to allow reuse of the bite bar. The bite bars prevented significant cranial movement relative to the camera.

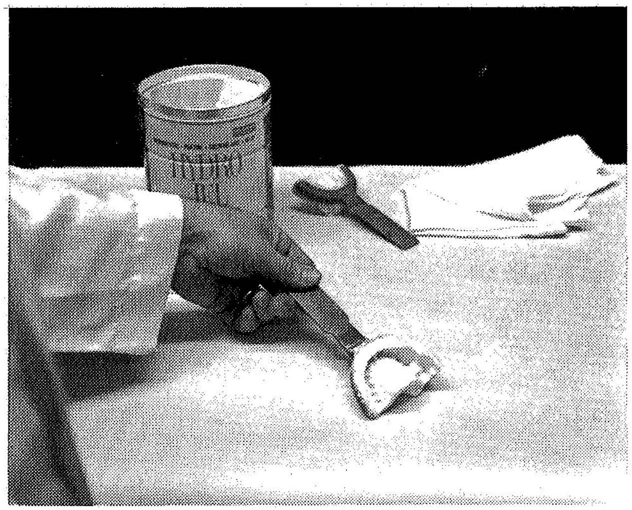


Figure C-2. Upper Dental Impression Attached to Bite Bar

A pair of springs were used to support the mass of the head restraint and camera for the Y-axis turns, the pair involving antagonists producing the balance required for smooth support of head turn. By precise vectoring of the spring tensions, the 10-pound mass of the camera complex was completely compensated.

The same basic test format was used as in Task II of NAS 9-5232. The subject was asked to perform a 10-trial RATER performance sequence in each of the six combinations of turn orientation and force field environment. Y-axis head turns with the turn plane at 0 to 45, and 90 degrees to the plane of the MRSSS rotating at 12.2 rpm and the same three orientations with perturbation of 0.1 cps, ±3 degrees added to the rotation.

Upon arrival at the MRSSS laboratory, the subject's dental impression was taken while he was being fitted with EOG and EKG electrodes. He was then trained on the RATER until his performance reached an asymptotic plateau.

The subject's EOG leads were then attached to Sanborn 150 polygraph and the EOG calibrated. For calibration, the subject was positioned at an American Optical Model 12230 perimeter and asked to execute a series of repetitive 5- and 10-degree visual excursions in rhythm with a one/second metronome beat, with the recorder at its slowest paper speed.

Next, the subject was placed in the test chair, the head restraint adjusted for comfort of head turns, and the bite bar placed in his mouth. The bite bar was rigidly bolted to the eye camera after it was determined that the camera complex was positioned so the corneal light source was reflected by the left eye of the subject and the reflected eye spot was satisfactorily focused and centered by the periscope onto the transparent frame of the calibration leader. Final centering and focusing of eye spot was done with the subject's gaze fixed directly on the collimated display of the RATER.

The eye camera's center was in the sagittal plane passing through the subject's left eye, but offset from the mid-sagittal plane of the subject. The off-the-shelf camera is designed so the optical axis of the camera and mid-sagittal plane of the subject converge at a point five feet in front of the camera. Since this convergence distance could not be easily shortened and it was desired that the subject's eye-to-display distance be kept in an operational range (one to two feet), the proximal surface of the RATER's collimator was laminated with a plastic square 18 inches on a side, divided into 1-inch squares. Figure C-3 is a series of positive prints from the 16-mm film; the white spot in each frame is the eye spot and the black oval in the lower right is the orifice of the RATER display. If the grid was five feet in front of the focal plane of the camera, with the subject fixed on the RATER display, the white spot would be superimposed on the black spot. But with convergence interrupted, calibration of the eye-motion camera proceeded as follows. Fixation points were inscribed on the grid surface at 1-inch intervals, vertically above and below, and horizontally to the left and right of the RATER display orifice (A, B, and C above, D, E, and F below, etc.). Displaced from the area where the subject would be fixing his gaze, but near the center of the field of regard (due to the camera offset), the same letters were duplicated in two short, parallel arrays. The strips read O-A-O-B-O-C-etc., the O symbolizing the RATER display orifice. A complete calibration sequence consisted of the on-board examiner audibly reciting the above order of letters to the one/second beat of the metronome while simultaneously designating each letter with a pencil and while the subject was visually fixing each letter. Both cinematographic (8 f/s) and electro-oculographic data were continuously recorded. Figure C-4 is composed of five frames from a representative eye motion camera calibration film photographed with normal ambient illumination, using Eastman 4-X 7224 film at f16 and 8 f/s. Viewing from left to right: eye movement from frame one to frame two is 3 degrees, from frame two to

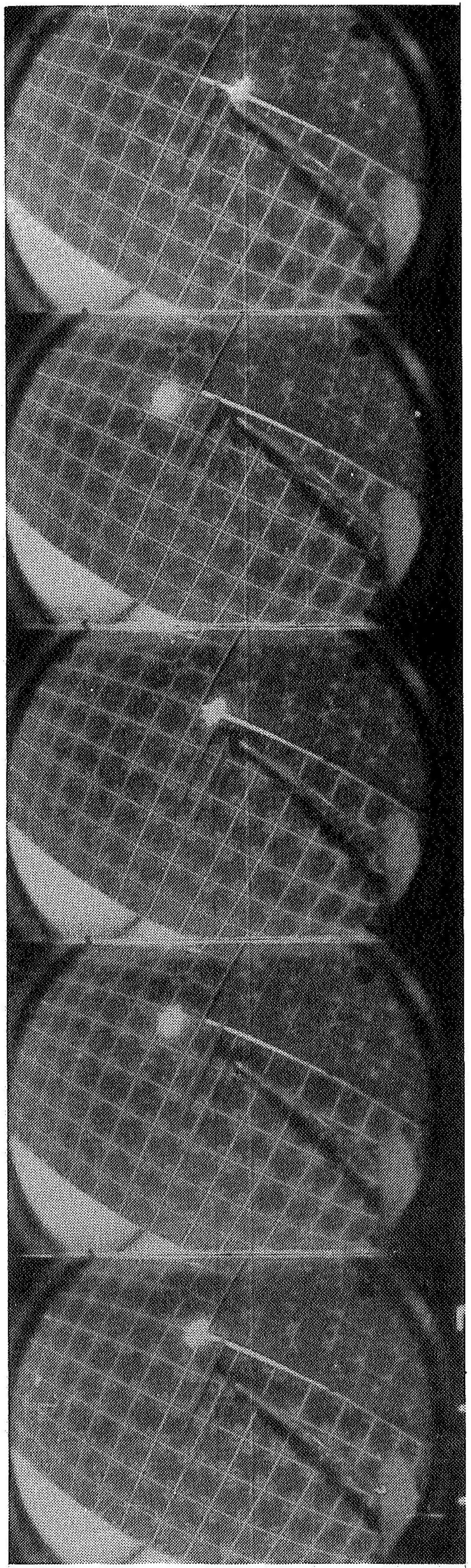


Figure C-3. Eye-Motion Camera Calibration Film

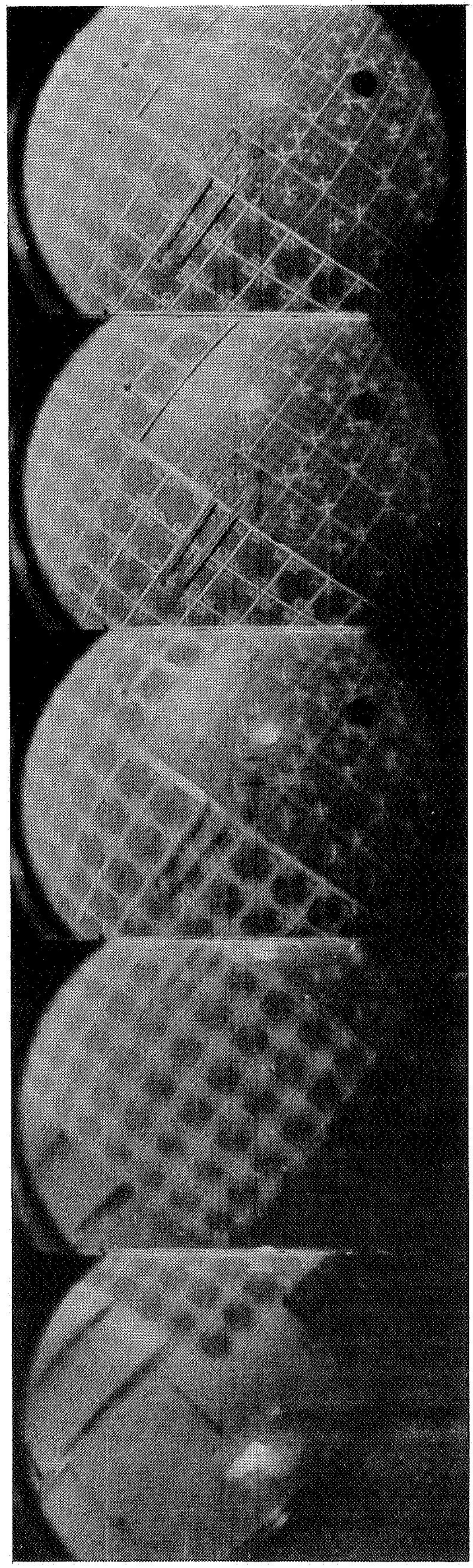


Figure C-4. Eye-Motion Camera Head Turn Film frame three is 6 degrees, and from frame four (RATER display) to frame five is 9 degrees. Diameter of entire field of regard is approximately 40 degrees of visual angle. Calibration grid squares measure one inch on a side.

A complete calibration sequence was run at the beginning of each test. The subject would not alter his position throughout a given test. However, as a reliability safeguard, a calibration leader was spliced in front of each 100-foot roll of film and a check made before each sequence to assure that the eye spot was sharply centered and focused.

During actual test sequences, limited film footage precluded running the camera continuously; therefore, control timing circuitry was programmed to start the camera as each trial started and to stop it as it ended. After each sequence the on-board examiner would unload the exposed film, reload the camera, and change the position of the test chair for the next sequence.

The head turn for all orientations was 70 degrees and the RATER was operated on the self-paced mode with the same button-color control-display combinations. The collimation index provided a 1 degree visual display.

Figure C-4 also shows a representative excerpt from a head-turn test film photographed with normal room illumination, using Eastman 4-X Type 7224 film at f11 and 8 f/s. Viewing from left to right and counting the frames from the beginning of the subject's head turn: the first picture is the second frame (2f), the second picture shows the eye spot about to disappear at right margin of camera field (5f), the eye spot has reappeared in the third picture (17f), and the fourth (20f) and fifth (23f) pictures show a stable field of regard but a -3 degree movement of eye spot.

Figure C-5 depicts a frame-by-frame analysis being made of a test film, using a Vanguard Model M16-10 (15X) Motion Analyzer. The first step in data analysis produced a series of single sheets of tracing paper, each bearing a complete record of the absolute eye spot movement during a single trial of a single subject. Figure C-6 shows a close-up of the single frame display, with superimposed tracing paper bearing a locus of points duplicating the eye spot positions in preceding frames.

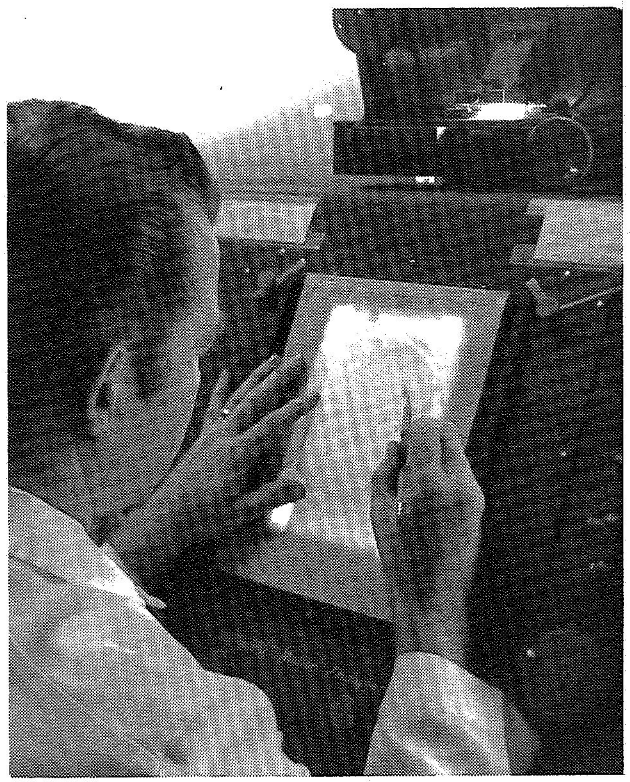


Figure C-5. Plotting Frame-by-Frame on Motion Analyzer

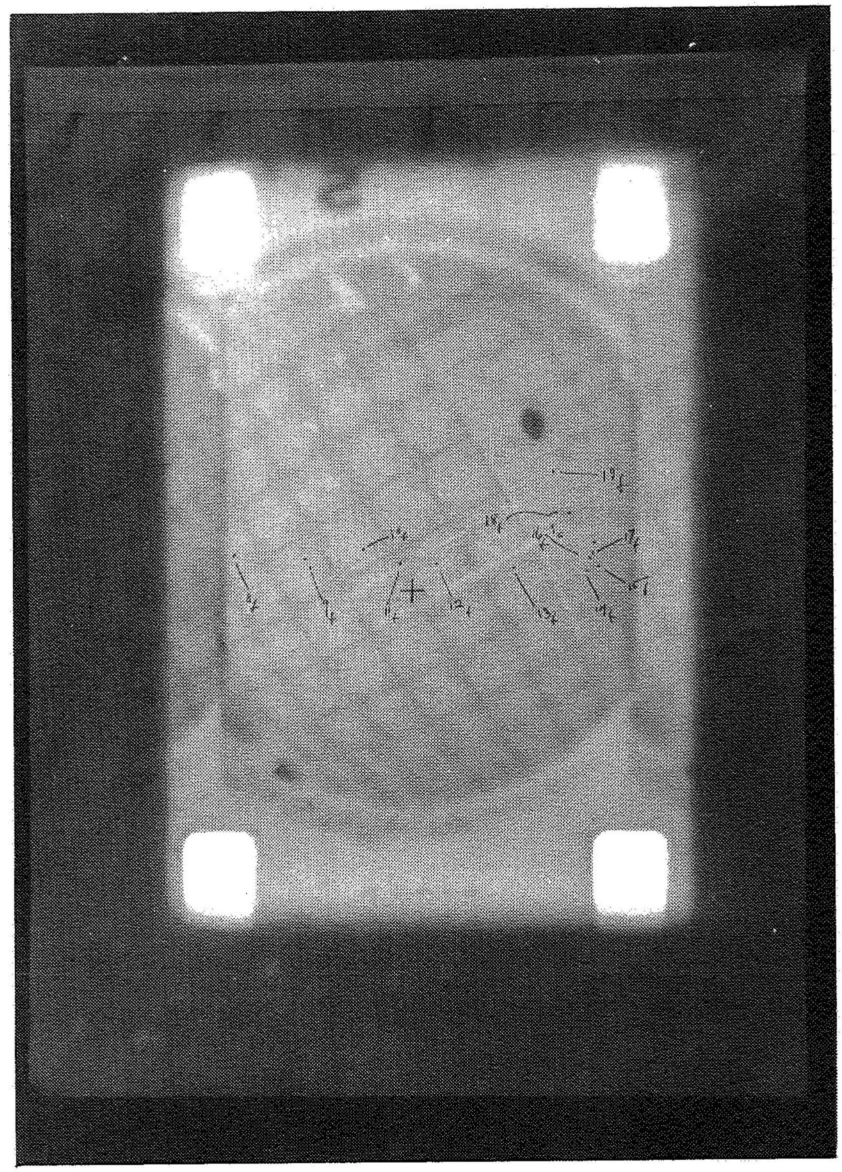


Figure C-6. Locus of Eye Spot Positions

APPENDIX D

THE VECTOROCULOGRAM

For a long time nystagmography has been a tool for the study of semicircular canal sensitivity. Proper positioning of the head produces relatively pure response of either the horizontal or vertical canals. Studies concerned with the canal response to cross-coupled accelerations that produce stimulation due to their gyroscopic effects are not usually confined to one axis and, in addition, various amounts of linear acceleration accompany the motion during the angular movement of the head. In order to quantitate the response to the stimulus using reflex eye motion, it is necessary to be able to measure the direction and amount of eye motion directly instead of just the horizontal and vertical projections of that movement. The first technique used was an eye motion photographic technique that simultaneously photographs the field of gaze and superimposes a light spot resulting from a reflected Purkinje image. With this apparatus it was possible to plot eye movement and measure the reaction to cross-coupled stimuli in terms of difficulty in fixating on a target light. The method is time-consuming, awkward, and the results are highly dependent upon the relative immobility of the eye spot light source which is sensitive to the forces of centrifugation and head movement.

As an alternative to the method described, the horizontal and vertical oculograms were analyzed and comparative total eye motions measured. Integration of these vertical and horizontal deflections into a single vector in real time offered an easier approach to the study of the eye fixation difficulty which is encountered following stimulation by a cross-coupled acceleration.

While researching this concept it was found that Ford and White[1] had previously proposed such an integration of oculograms for military fire control guidance, and since that time development of the dual-beam oscilloscope has greatly simplified the task by incorporating all the necessary electronics in a single instrument. Borschein and Shubert have used the integration of horizontal and vertical oculograms to determine direction of nystagmus produced by cross-coupled accelerations[2]; they refer to their method as "Vector Nystagmograms."

Vertical and horizontal EOG signals from Beckman bio-electrodes were fed directly into the oscilloscope with a point of light resulting on the CRT. The subject was then placed before a standard perimeter and the zero point adjusted so the spot was at the center of the scope grid when the subject was using his primary axis of fixation. The exact point of gaze could then be determined from the scope. With further experience it was found that an improved signal-to-noise ratio resulted when two Kintel 114A amplifiers were used to increase gain near the signal source before transmitting through the centrifuge sliprings to a Tektronix 502 or 503 scope in the control room.

A television camera was used to record the scope spot from the CRT grid. To correlate this information with the previous eye camera work, simultaneous photos and oculograms were taken. Multiple TV cameras were used to record camera film frame number, vertical and horizontal EOG tracings, and the integrated "VOG" signal from the scope. These were all mixed by a special effects generator to present a single video picture incorporating all the desired information (schematic shown in Figure D-1). The video tape information was then transferred to kinescope form for analysis (as shown in Figure D-2) and permanent retention. Frame-by-frame comparison of eye motion was then plotted from corresponding eye photographs and the VOG.

Present experiments have taken the technique one step further. Instead of recording the signal from the scope by camera, the EOG output is fed into a Moseley 7035A X-Y plotter, making the scope redundant but still convenient for system calibration. All eye motion associated with a single head turn is recorded on a single X-Y plot, the time delay constant being adjusted to provide a smooth recording.

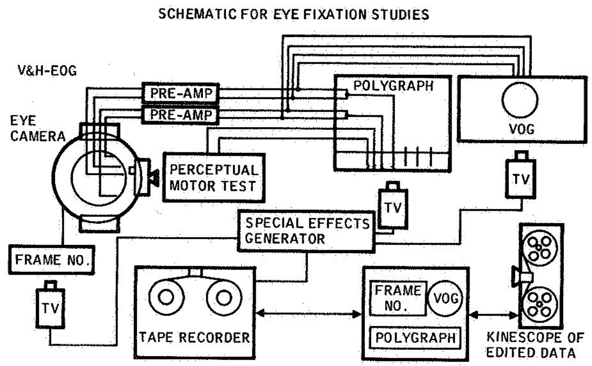


Figure D-1. Schematic for Eye-Fixation Studies

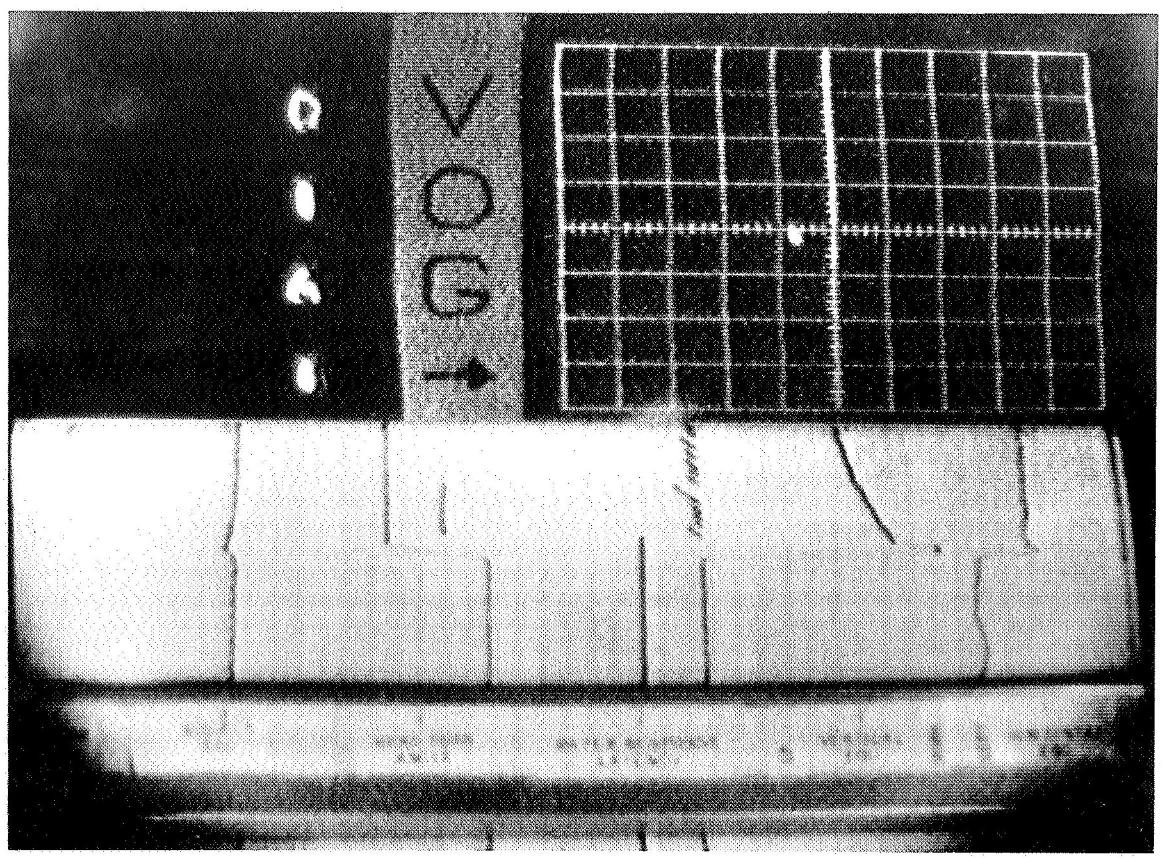


Figure D-2. Kinescope Form of VOG

This method of recording eye motion is particularly applicable to the study of cross-coupled accelerations. In such accelerations the subject is always rotating in some manner through the plane of environmental spin. Consequently, there is a continuous change in the semicircular canal being stimulated and this results in a change of the eye axis motion that is used to determine semicircular canal activity. A seated subject on a centrifuge facing the center of rotation will, upon initiation of an X-axis head turn, elicit a Y-axis illusion because this is the plane of the cross-coupled acceleration. As he continues the head turn, however, his axis of displaced rotation (with respect to his head) changes from a Z to an axis between Z and Y so a roll and yaw component will be added to the illusion. Vertical and horizontal nystagmus recordings will show this as a decrease in the initial vertical amplitude, with a component appearing on the horizontal recording. On return of the head, the vertical recording will again increase, giving a confusing picture of a greater response on return of the head than on the original turn but really due only to the vector arrangement of the stimulus. The VOG on the other hand will give a smooth curve of eye motion with a characteristic amplitude for such a head motion when the subject is fixating on a point of light.

REFERENCE

1. Ford, A. and C. T. White, "Electro-Oculography in Human Servo Control", Proc. of the Third Internat. Conf. on Medical Electronics, London, 1960.

2. Borschein, H. and G. Schubert, "The Direction of Vestibular Coriolis Reaction", Zeitschrift für Biologie, Vol. 113, No. 2, 1962, pages 145-160.